Higgs in Di-photon Channel

Yuri Gershtein

Outline

- Current results
  - MVA techniques (and model dependence they produce) *aka* squeezing blood from stone
  - SM-like analysis
  - FP-like analysis
- What's coming
  - how to measure VBF with minimal systematic error from ggH contribution?
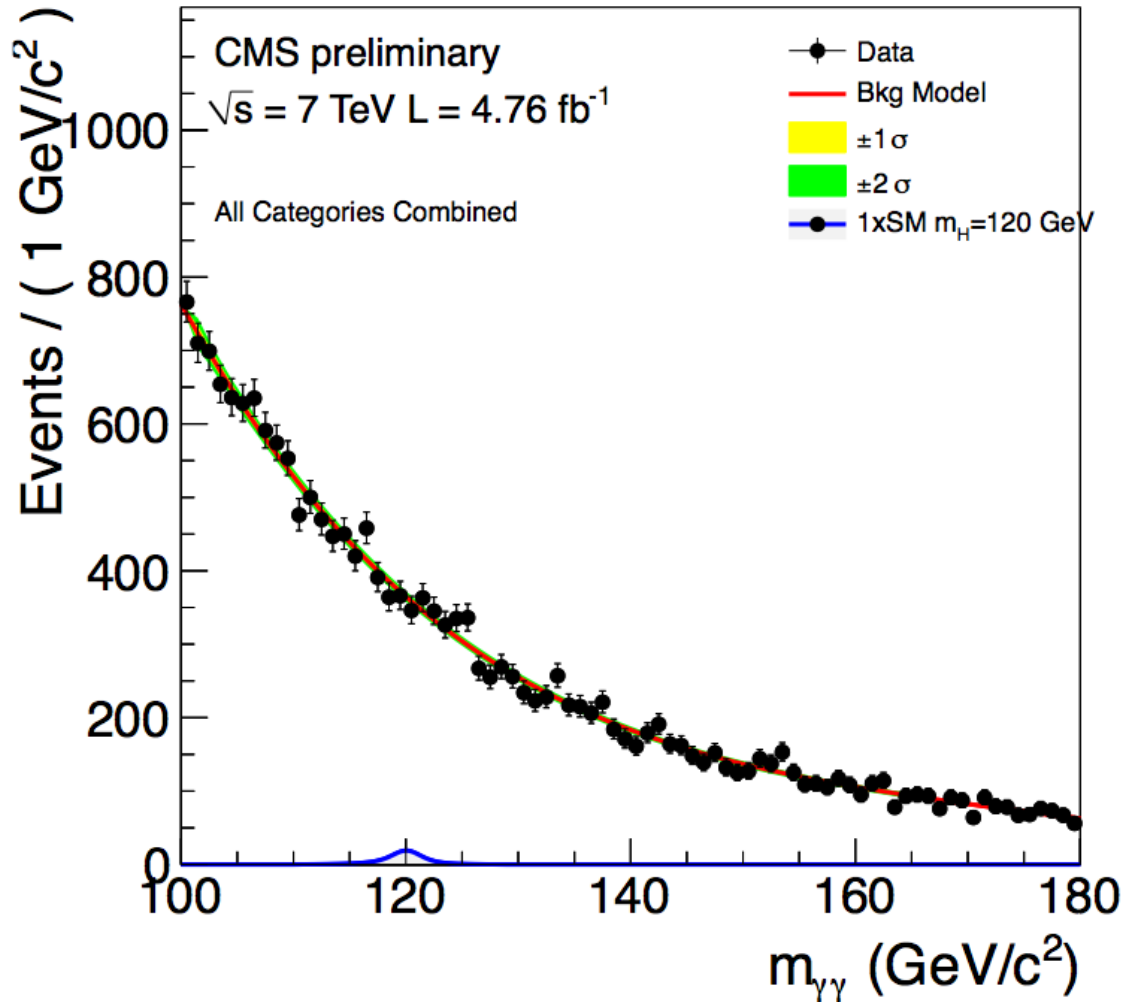
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H→γγ Search

- Main idea: measure energy of the two photons and their opening angle

$$M = \sqrt{2E_1E_2(1-\cos\alpha)}$$

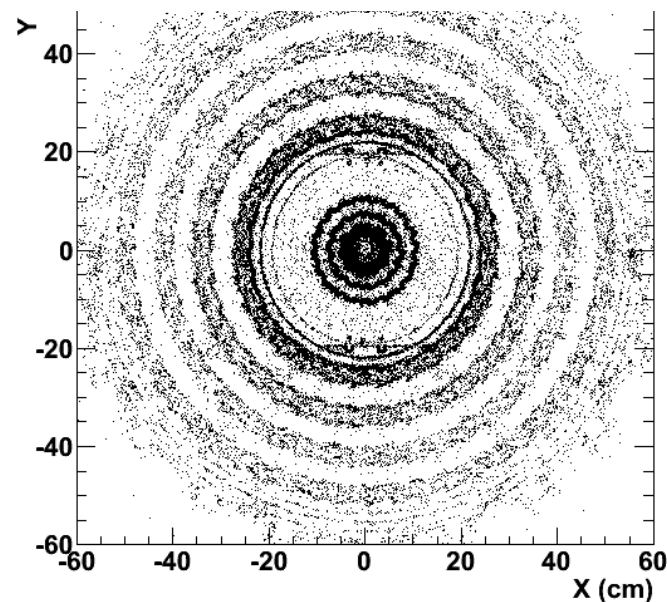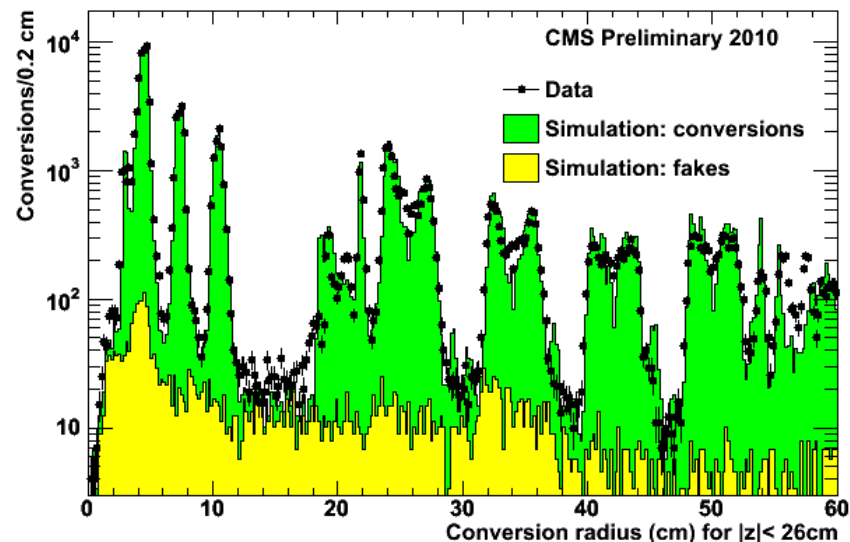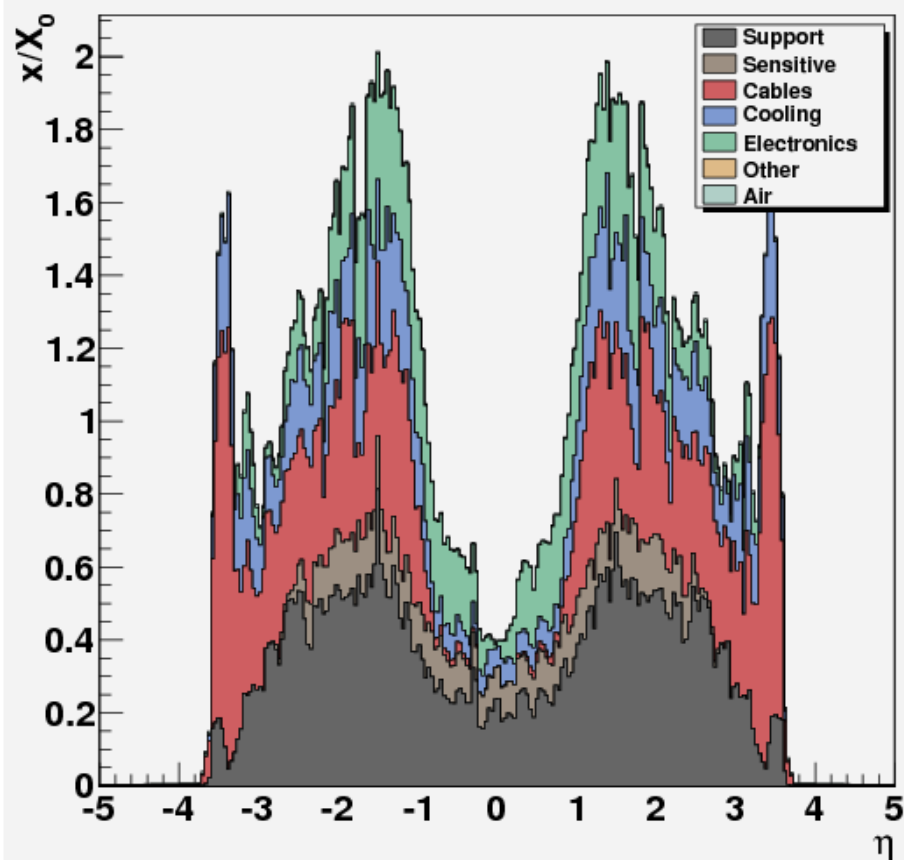- How come this is hard?!

The Challenge

- Huge "irreducible" background from QCD di-photon production (plus instrumental backgrounds)

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Tracker Material

- Reasonably well described by simulation
- Degrades energy resolution

Material Budget Tracker

CMS Preliminary 2010

The First Squeeze

- Improve photon energy resolution
- Energy resolution is affected by
  - Impact point in the calorimeter (containment)
  - Whether the photon converted
  - Radius of conversion
  - The amount of material that electrons from conversion have to traverse before impacting calorimeter
- Very non-trivial correlations between measured photon properties and the corrections that one needs to apply
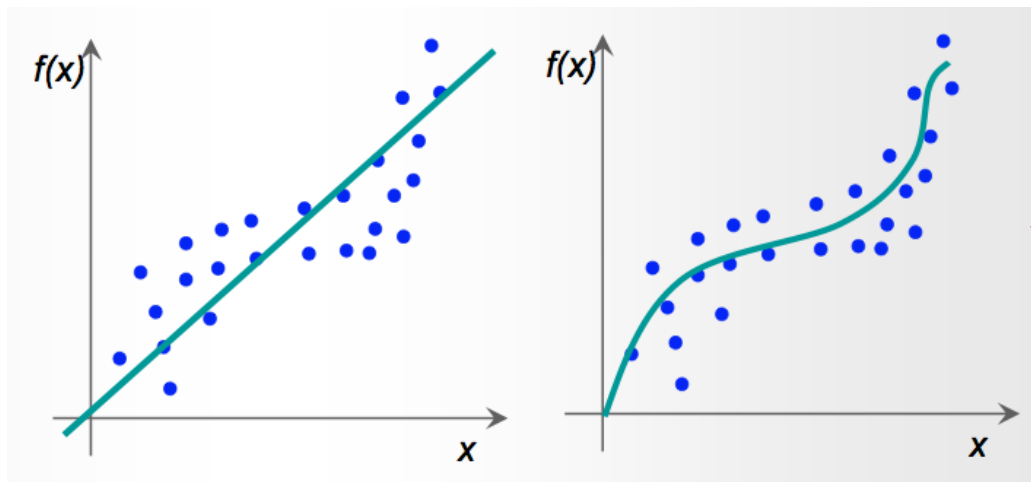
"trivial" in one dimension
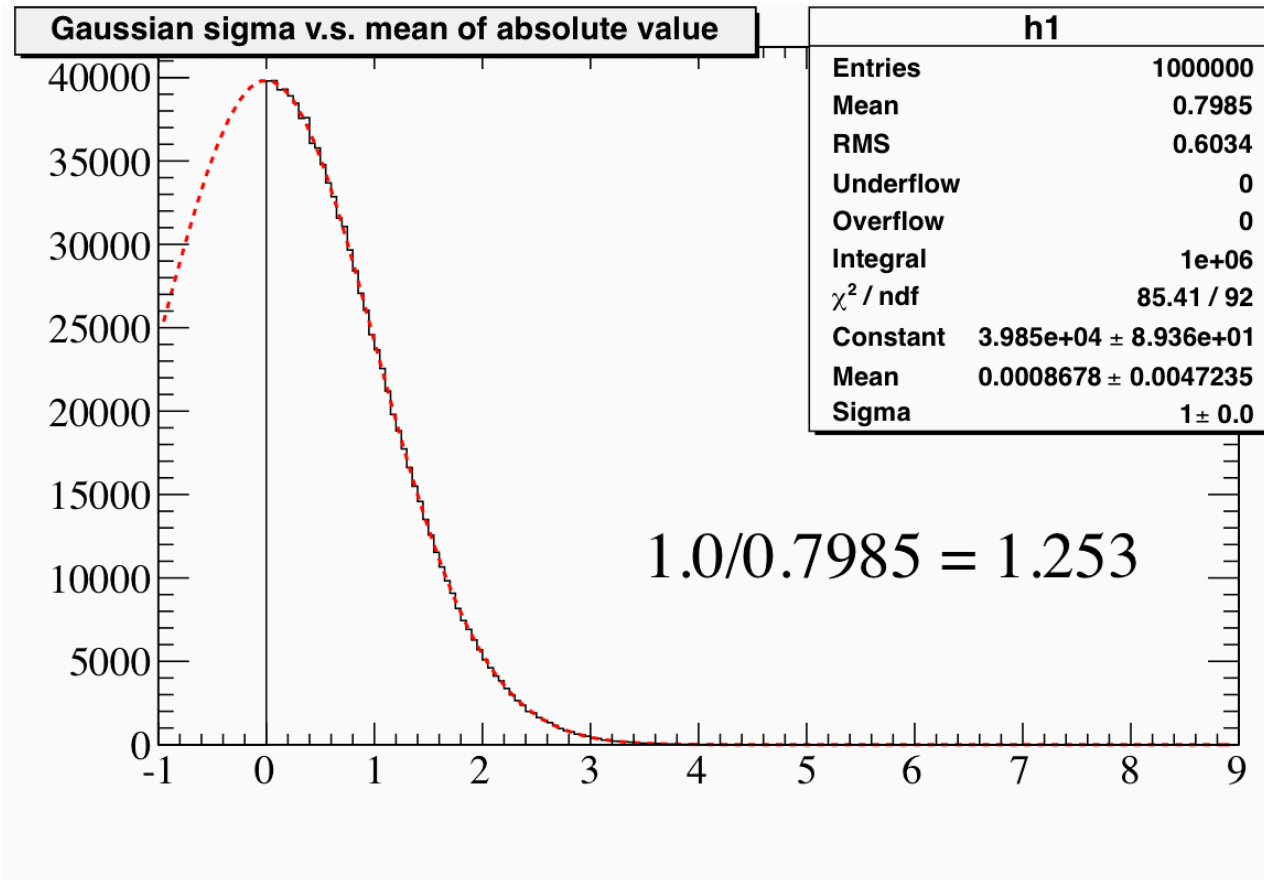
The First Squeeze

- Improve photon energy resolution

- Energy resolution is affected by
  - Impact point in the calorimeter (containment)
  - Whether the photon converted
  - Radius of conversion
  - The amount of material that electrons from conversion have to traverse before impacting calorimeter

- Depending on the region in the detector, can achieve up to 20% improvement in resolution compared to "standard" factorized correction method
  - And can check that the used variables and their correlations are described by simulation by comparing electrons from Z decays in data and MC
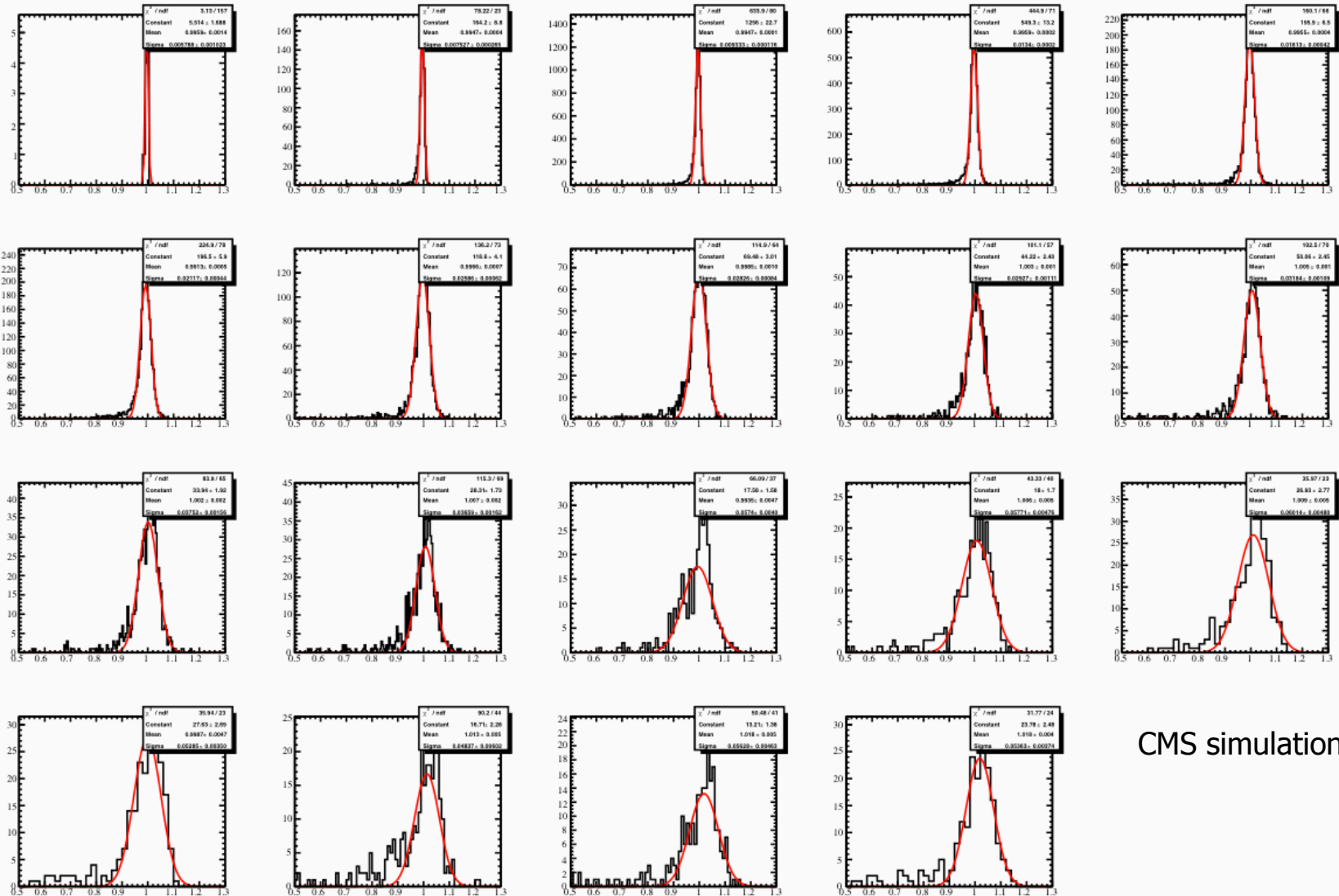
The Second Squeeze

- Some photons are measured well, some are not – instead of mixing all events together, can we separate them into classes and combine the searches in individual classes?

- First 5/fb result – just 2 variables: Barrel – Endcap and converted-unconverted based on shower narrowness (fraction of cluster energy in the 3x3 crystal matrix)

- Train the second regression – this time do not try to improve the resolution by asking BDT to guess the energy, ask the BDT to guess how well this particular photon is measured

  - Same variables as for energy regression
  - Different target – instead of E_{true}/E_{reco} regress to $|(E_{reco}-E_{true})/E_{true}|$

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Regression to resolution

- Regress to |Ereco-Etrue|/Etrue
  - average value of that is 0.7985 of gaussian sigma

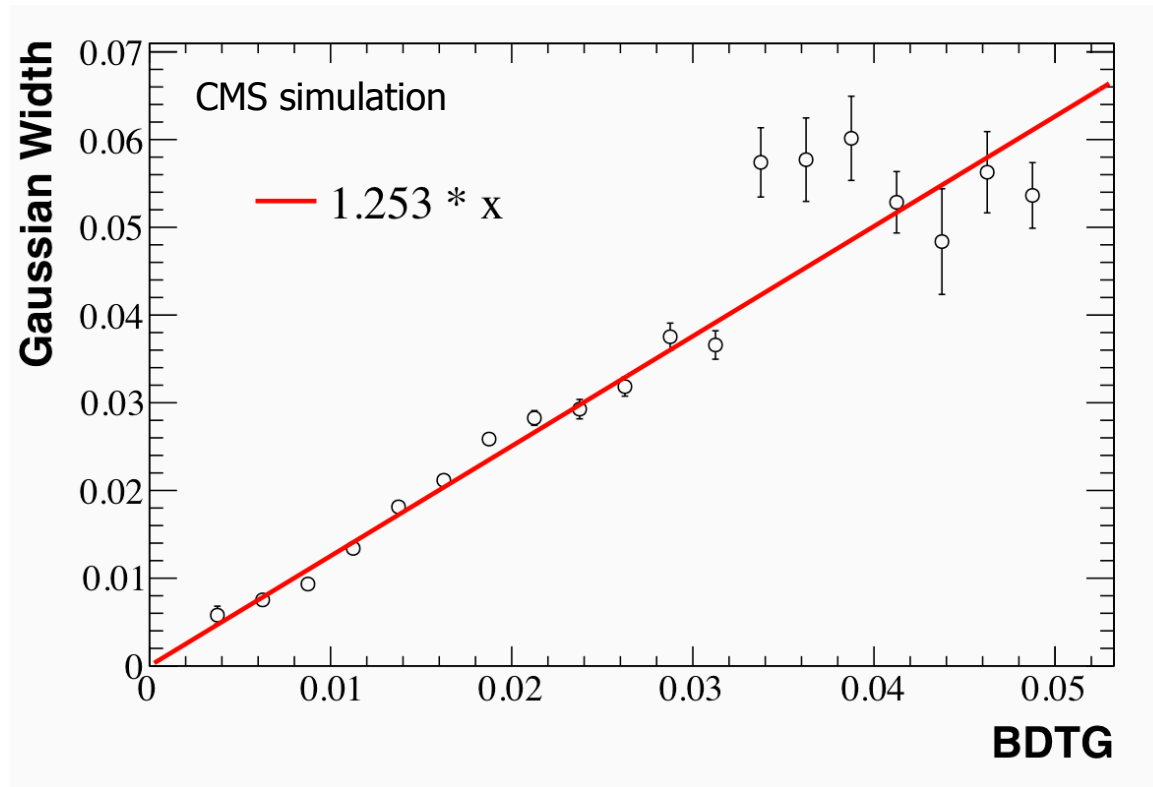| Gaussian sigma v.s. mean of absolute value	h1	
	Entries	1000000
	Mean	0.7985
	RMS	0.6034
	Underflow	0
	Overflow	0
	Integral	1e+06
	χ^2 / ndf	85.41 / 92
	Constant	3.985e+04 ± 8.936e+01
	Mean	0.0008678 ± 0.0047235
	Sigma	1 ± 0.0

$$1.0/0.7985 = 1.253$$

Fit resolution in bins of BDT

CMS simulation

Fit resolution in bins of BDTG

Just as with energy regression, we can check the resolution regression using observed width of Z→ee

H→γγ resolution classification

- Mass resolution depends on the energy resolution of the photons and on the precision of the opening angle measurement

$$M = \sqrt{2E_1 E_2 (1 - \cos\alpha)}$$

- If the vertex is reconstructed correctly (within ~1cm) the contribution of angle in mass resolution is negligible
- If not, angular resolution dominates

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Choosing the right vertex
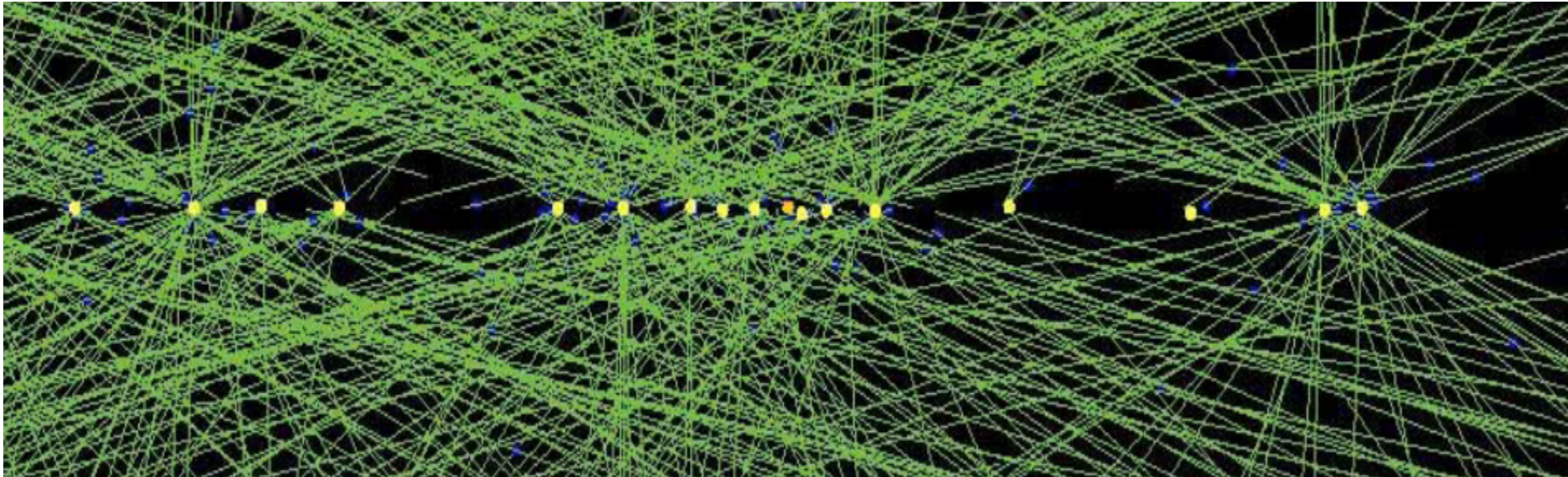
- Track activity in the best events – with no photon conversion – look very similar to a minimum bias event

The Third Squeeze

- Use BDT to choose the "signal" vertex
- For all events
  - "intensity" of the vertex $\sum \left| \vec{p}_T \right|^2$
  - tracks should follow direction of higgs recoil $\sum \vec{p}_T \cdot \dfrac{\vec{p}_T^{\,\gamma\gamma}}{\left| \vec{p}_T^{\,\gamma\gamma} \right|}$
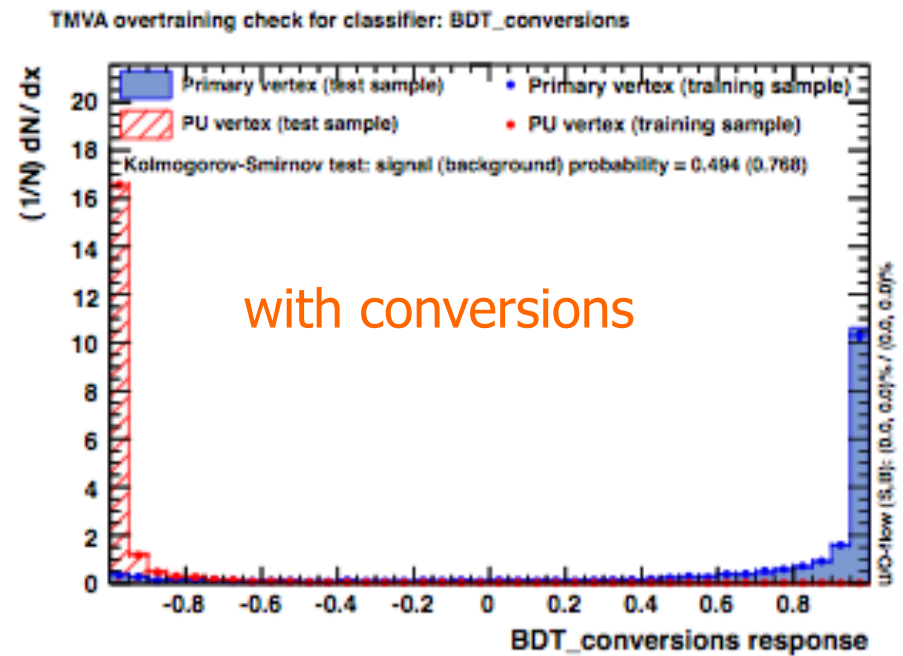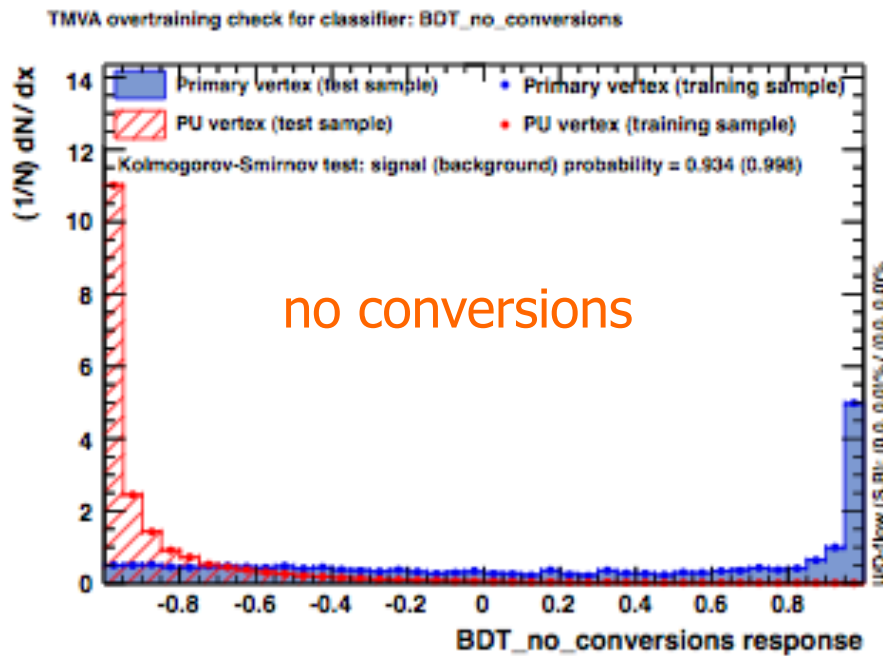 - track sum should be similar to higgs recoil $\dfrac{\left| \sum \vec{p}_T \right| - \left| \vec{p}_T^{\,\gamma\gamma} \right|}{\left| \sum \vec{p}_T \right| + \left| \vec{p}_T^{\,\gamma\gamma} \right|}$
- For events with at least one reconstructed conversion

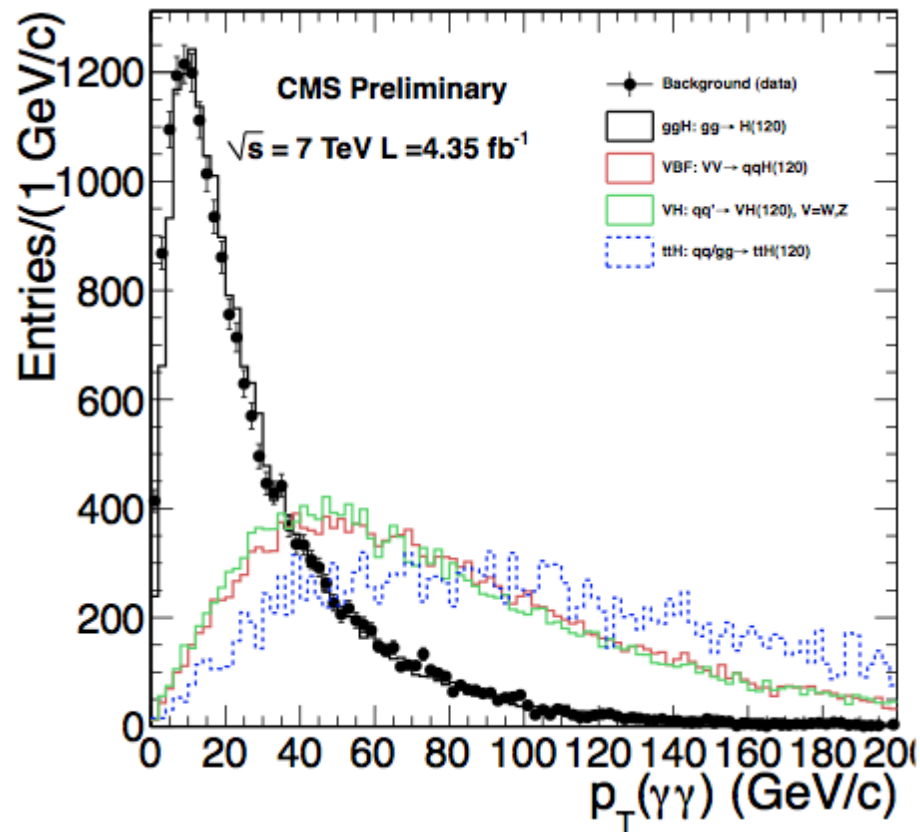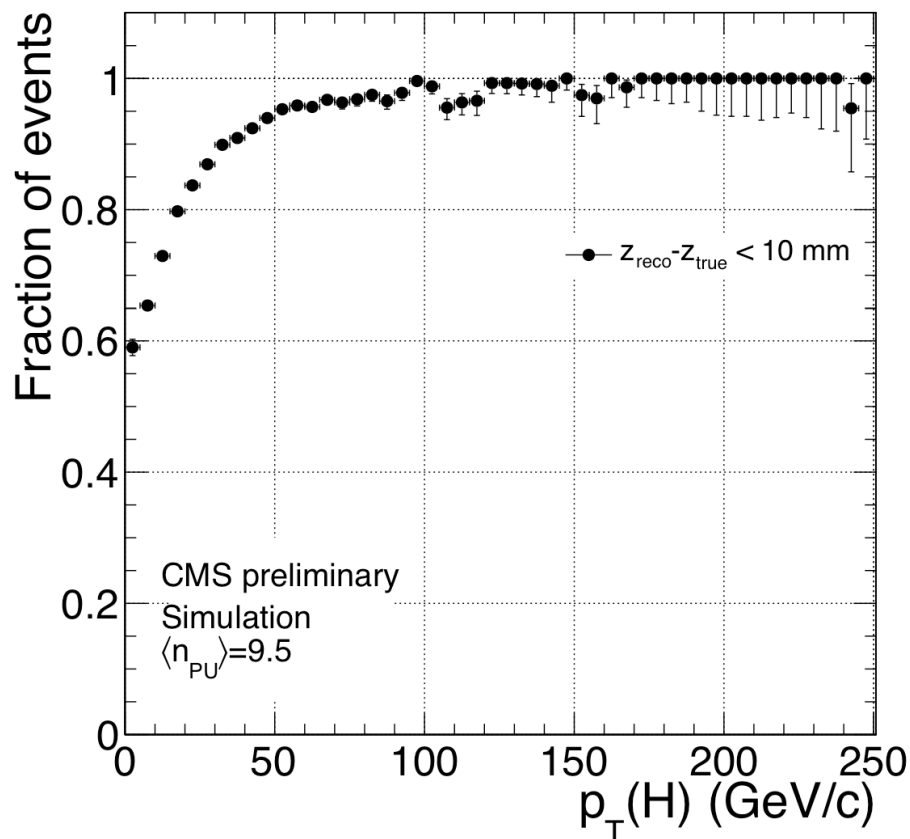 - "pull" $\dfrac{\left| z_{vtx} - z_{conv} \right|}{\sigma_{conv}}$

The Third Squeeze

- Simulation result on the Higgs signal sample

The Third Squeeze

- Total efficiency to get the right vertex ~83%
  - Validated with $Z \rightarrow \mu\mu$ and γ+jet events in data
- Higgs p_T is a good predictor of whether the vertex is correct
  - But is it the best one?

The Fourth Squeeze

- Instead of using one variable to predict the probability that the vertex is picked correctly, use an MVA (BDT)
  - p_T of the di-photon system
  - number of vertices
  - per-vertex BDT values for the best three vertices
  - Δz between first and second and third vertices
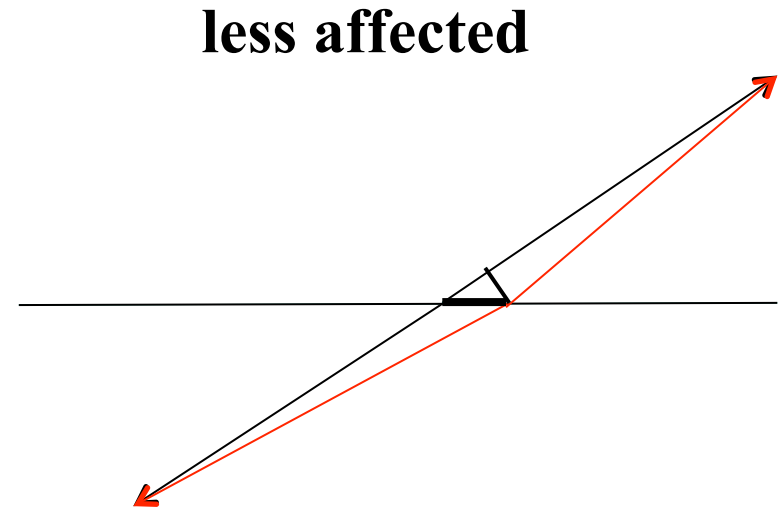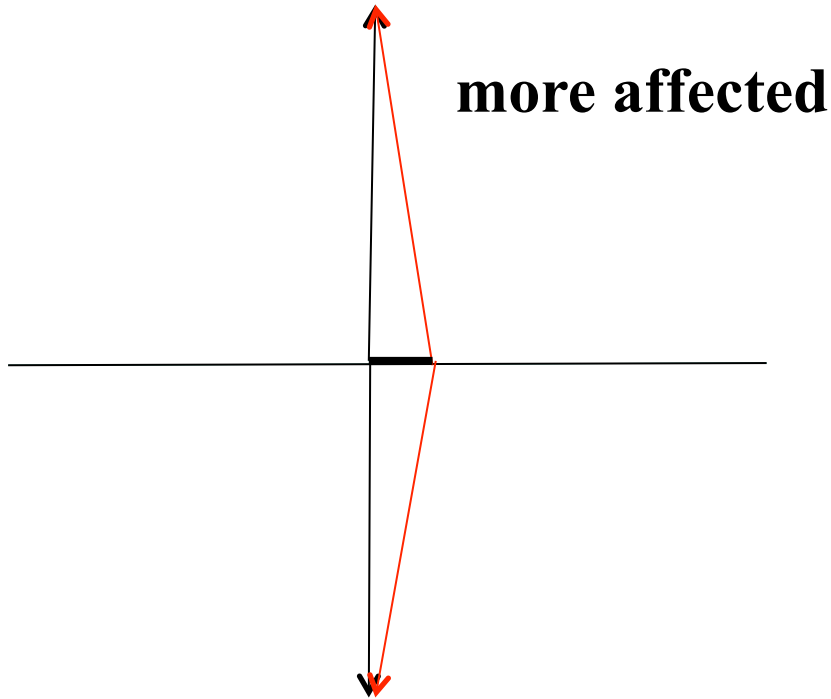 - "pulls" of the reconstructed conversions $\dfrac{\left|z_{vtx} - z_{conv}\right|}{\sigma_{conv}}$
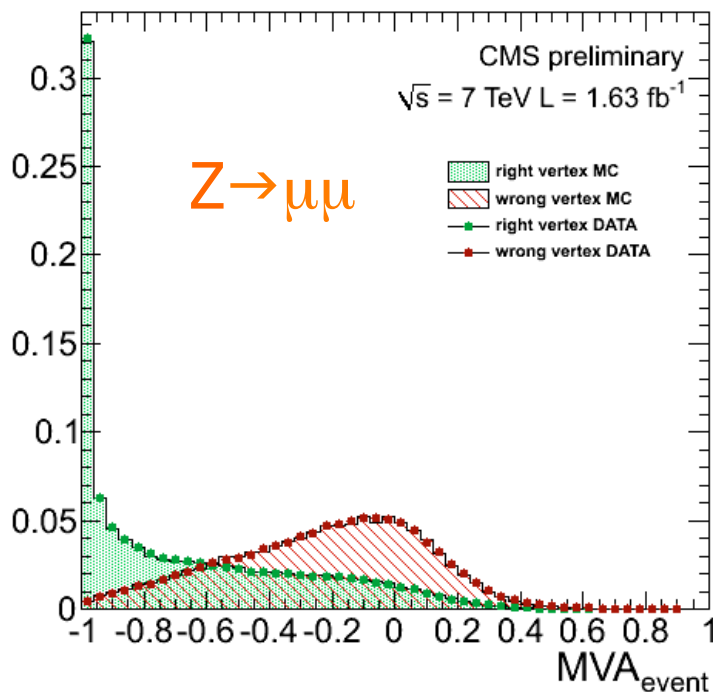
vertex impact on mass resolution

- Toy MC: take ideal energy resolution, and *always* pick a wrong vertex
  - The error is on 1-cosα, so back-to-back configuration is less affected
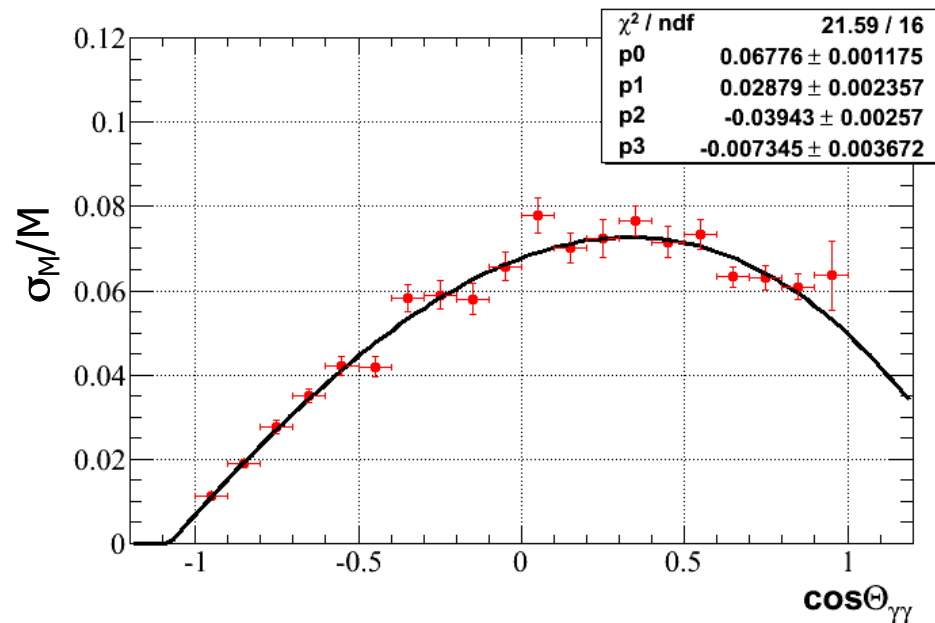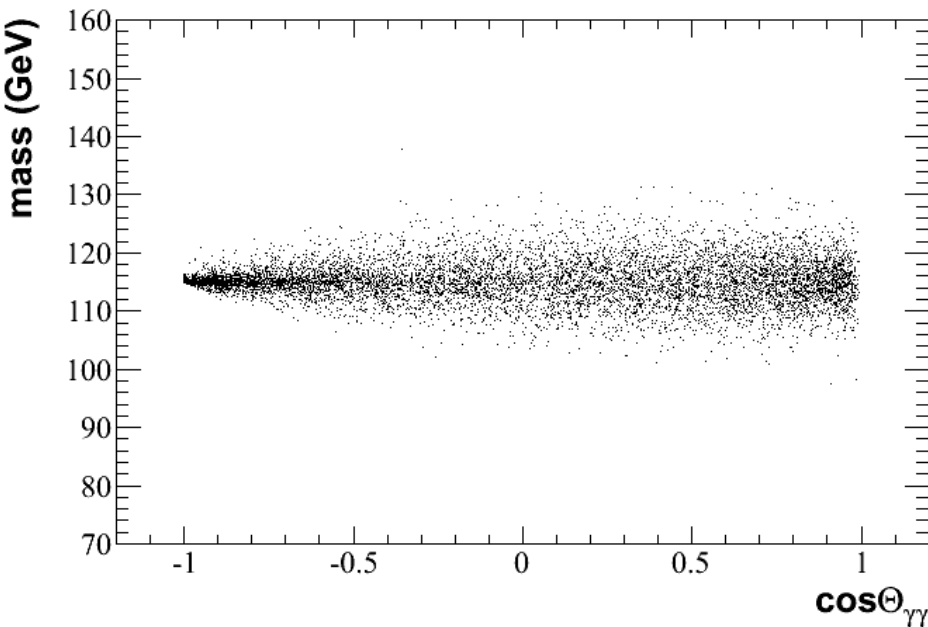
vertex impact on mass resolution

- Resolution also depends on the polar angles of the photons

more affected   **less affected**

vertex impact on mass resolution

- In fact, it turns out that this resolution can be calculated analytically

$$\frac{\delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2} \left| \frac{\operatorname{sech}\eta_{\gamma_1}\left[\operatorname{sech}\eta_{\gamma_1}\tanh\eta_{\gamma_2} - \tanh\eta_{\gamma_1}\operatorname{sech}\eta_{\gamma_2}\cos(\phi_{\gamma_1} - \phi_{\gamma_2})\right]}{1 - \tanh\eta_{\gamma_1}\tanh\eta_{\gamma_2} - \operatorname{sech}\eta_{\gamma_1}\operatorname{sech}\eta_{\gamma_2}\cos(\phi_{\gamma_1} - \phi_{\gamma_2})}\frac{\delta z}{r_{\gamma_1}} \right.$$

$$\left. + \frac{\operatorname{sech}\eta_{\gamma_2}\left[\operatorname{sech}\eta_{\gamma_2}\tanh\eta_{\gamma_1} - \tanh\eta_{\gamma_2}\operatorname{sech}\eta_{\gamma_1}\cos(\phi_{\gamma_1} - \phi_{\gamma_2})\right]}{1 - \tanh\eta_{\gamma_2}\tanh\eta_{\gamma_1} - \operatorname{sech}\eta_{\gamma_2}\operatorname{sech}\eta_{\gamma_1}\cos(\phi_{\gamma_1} - \phi_{\gamma_2})}\frac{\delta z}{r_{\gamma_2}} \right|$$

as a function of photon's η, ϕ, and the distance from (0,0,0) to ECAL cluster **r**

- This formula simplifies if **$r_1 = r_2$**

$$\frac{\delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left| \tanh\eta_{\gamma_1} + \tanh\eta_{\gamma_2} \right|\frac{\delta z}{r}$$

The story so far

- Minimized mass resolution
    - regression to energy
    - categorization of the vertices
- Evaluated mass resolution precision
    - regression to energy resolution
    - regression to vertex selection probability
    - analytical formula for resolution due to incorrect vertex

The story so far

- Minimized mass resolution
  - regression to energy
  - categorization of the vertices
- Evaluated mass resolution precision
  - regression to energy resolution
  - regression to vertex selection probability
  - analytical formula for resolution due to incorrect vertex
- <u>Left to do:</u>
  - Suppress instrumental backgrounds (photon ID)
  - Identify differences in kinematical features of signal and background and make a final discriminant optimizing signal-to-background ratio
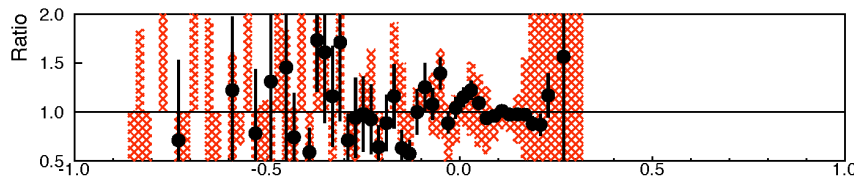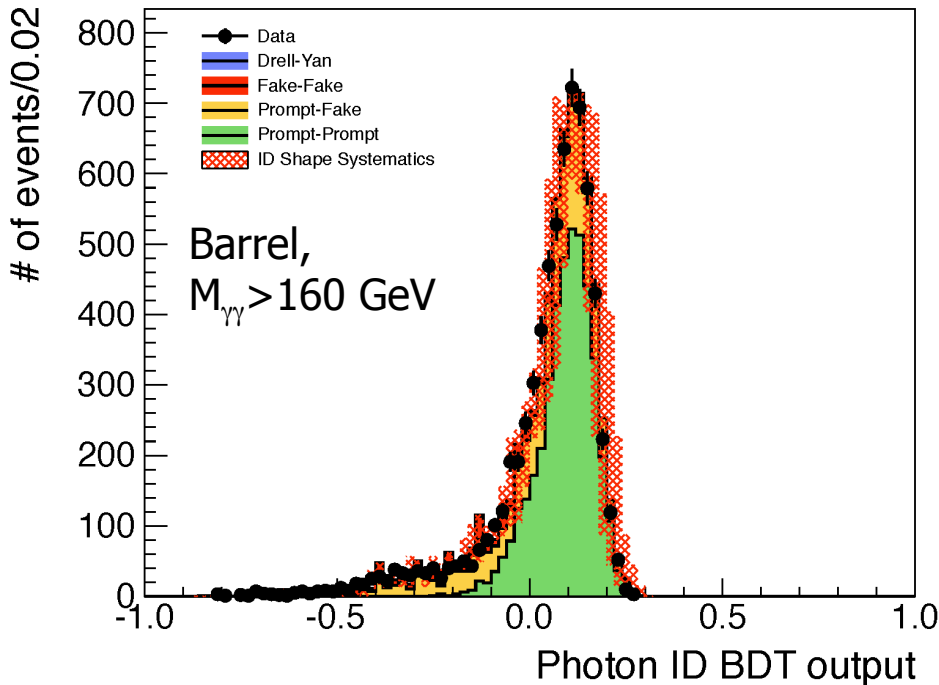
Instrumental Backgrounds

- From previous (non-MVA) analysis:
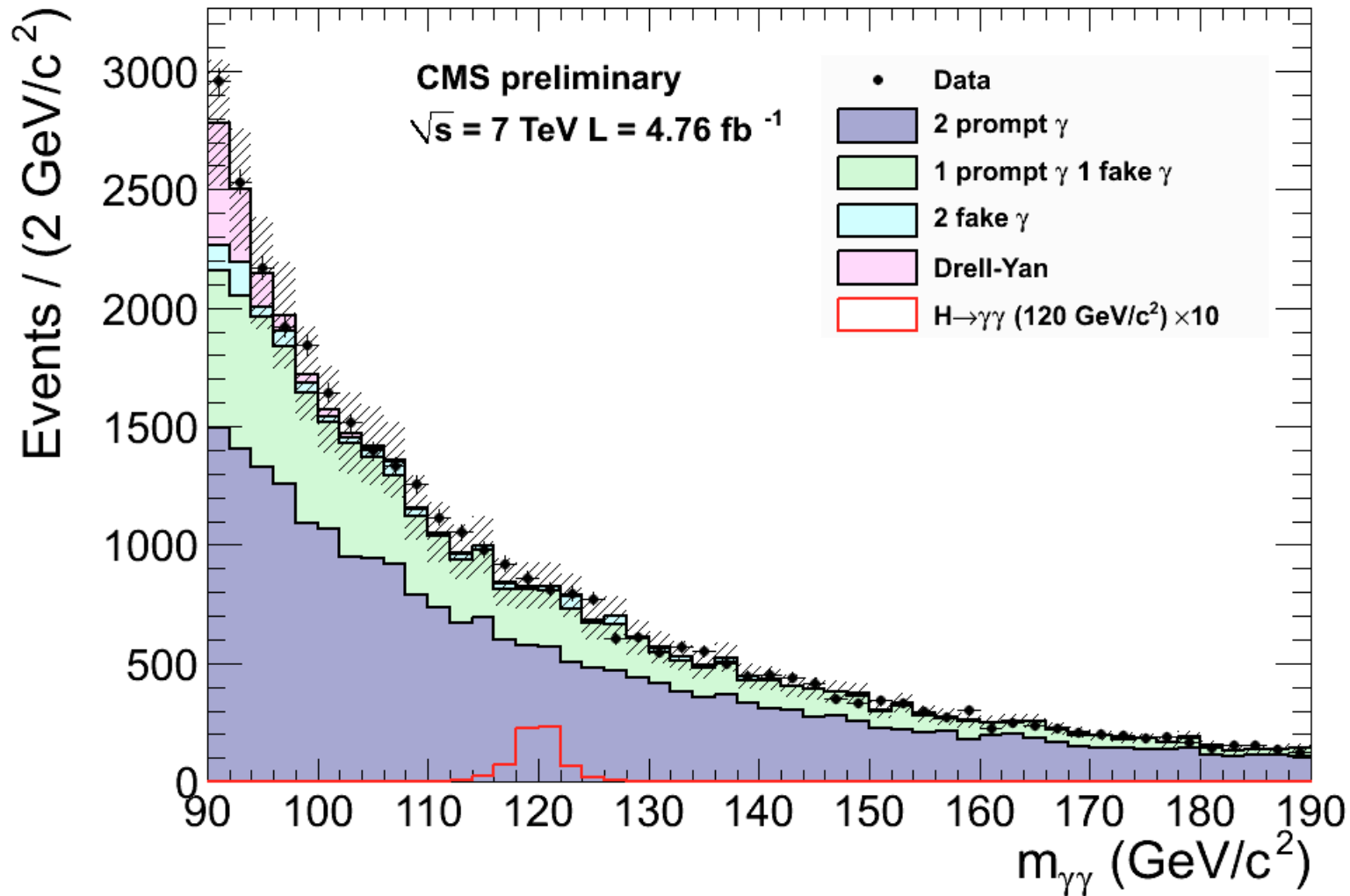
Photon ID MVA

- Garden variety classification BDT
  - Shower shape variables
  - Isolation variables
  - Underlying event activity
  - Cluster rapidity
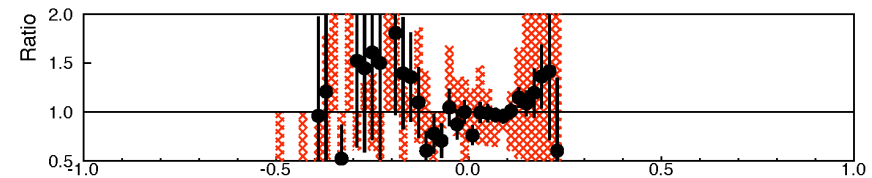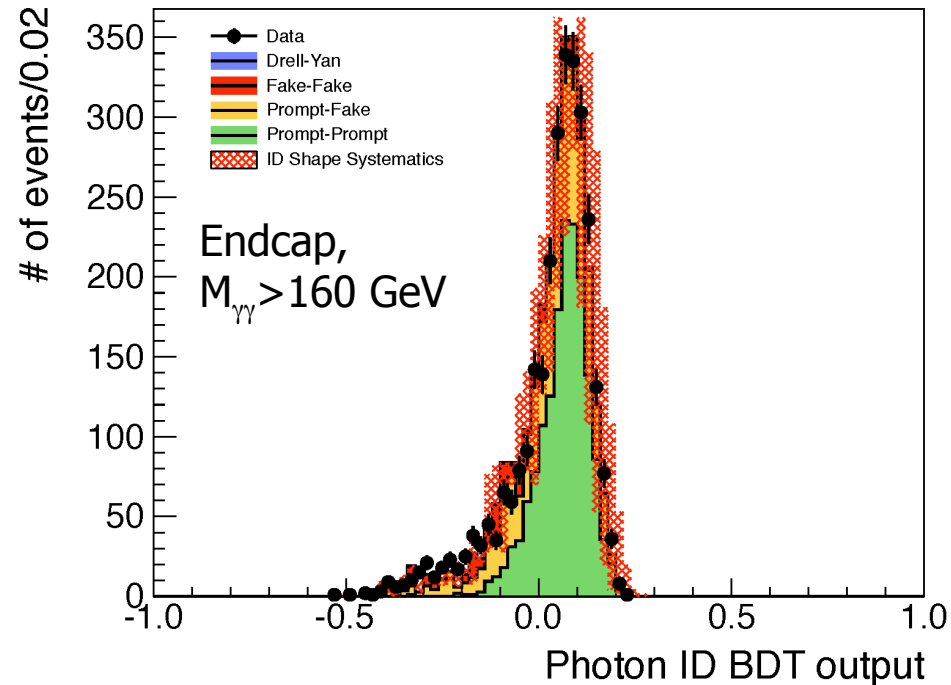
Final Squeeze:
putting everything together into the classification MVA

- **Kinematics**
  - $p_T^\gamma / m_{\gamma\gamma}$ for both photons
  - pesudo-rapidities of both photons
  - cosine of opening angle in azimuthal plane
- **Instrumental background**
 - Photon ID BDT values for both photons
- **Mass resolution**
  - for correct vertex choice
  - for incorrect vertex choice
  - probability of the vertex to be chosen correctly
  - Events need to be weighted so that best resolution events get higher classifier values

$$w_{sig} = \frac{p_{vtx}}{\sigma_m^{right}/m_{\gamma\gamma}} + \frac{1 - p_{vtx}}{\sigma_m^{wrong}/m_{\gamma\gamma}}$$
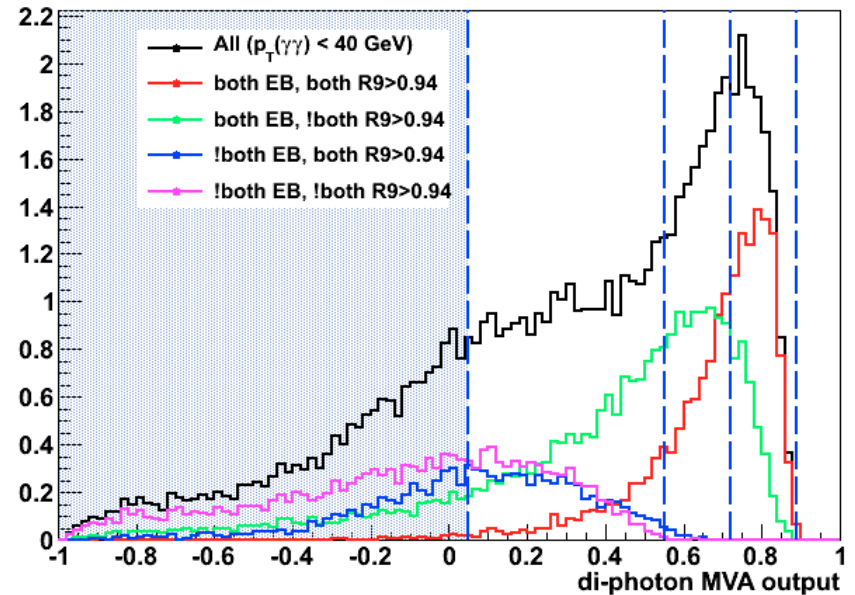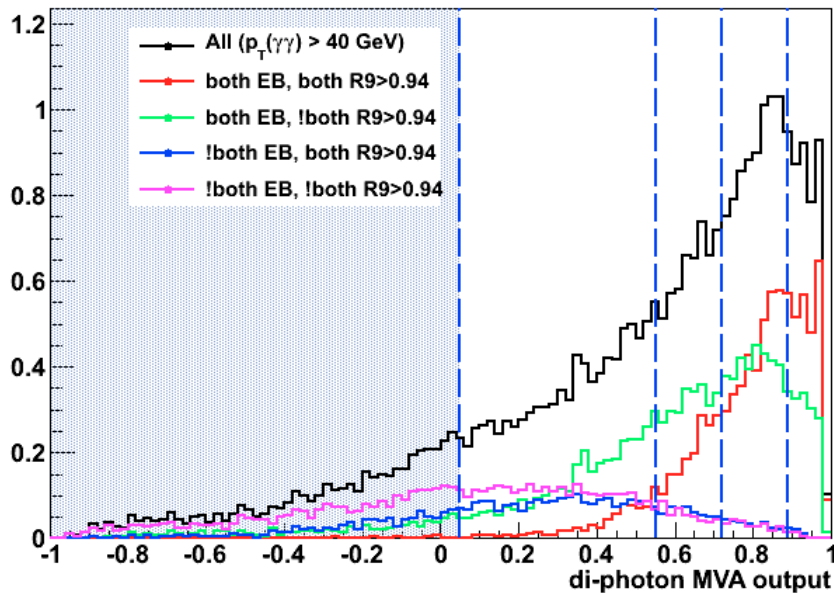
Final Classification

- Although data-MC agreement is very good, strictly speaking it is not necessary for background. It just shows that training is close to optimal

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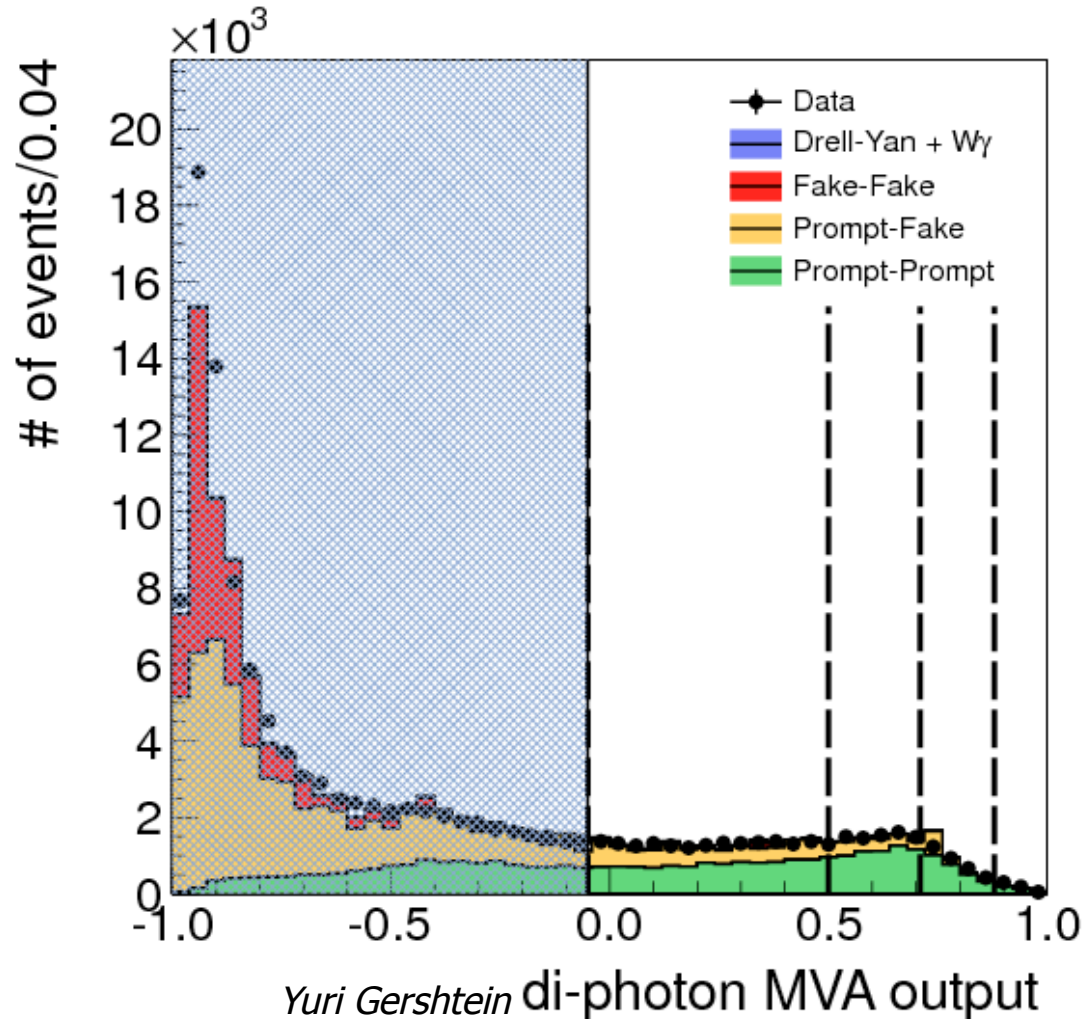
Final Classification

- Demonstration of what final classifier is sensitive to:
  - separate Higgs MC events into high/low di-photon pT
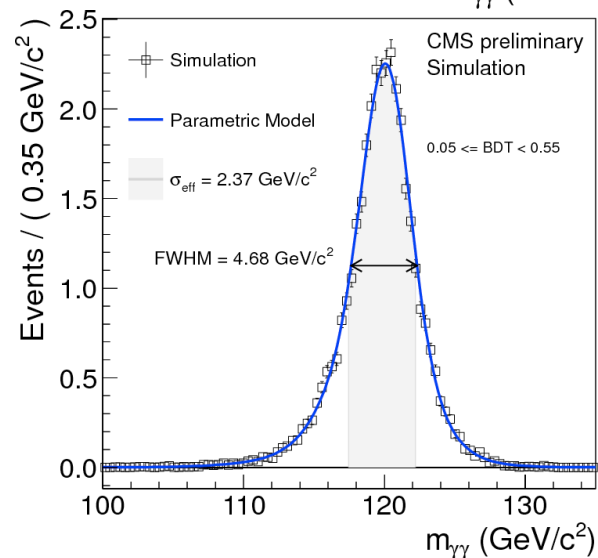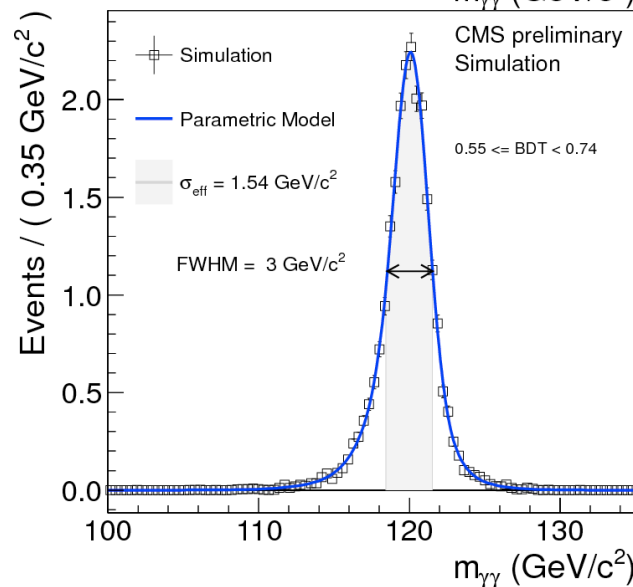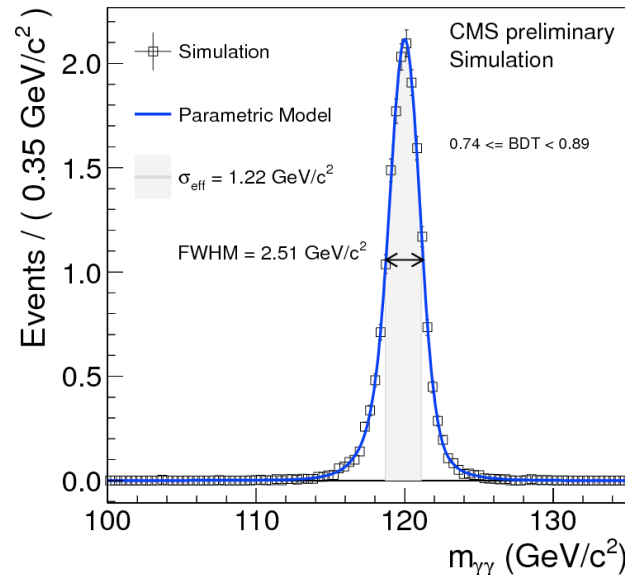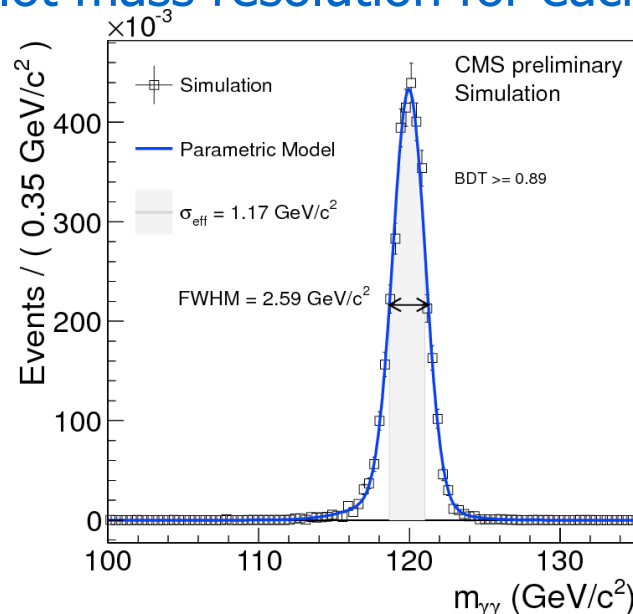

- Vertical lines correspond to optimized classifier bins
- Colored histograms are event classes as in non-MVA analysis
  - Note overlaps between the old categories!

Final Classification

- Demonstration of what final classifier is sensitive to:
  - plot mass resolution for each classifier bin (this is for 7 TeV)

VBF categories

- Events passing di-jet VBF tag are removed from untagged events and considered separately
- Different for 2011 and 2012 data
  - High PU conditions increase events where one of the VBF jets comes from ggH and the other from PU (tracking only goes down to 2.5)
- VBF tag definition 2011:
  - $p_T^\gamma > m_{\gamma\gamma}/2.18$, $m_{\gamma\gamma}/4$, $|\eta|<1.44$ or $1.57<|\eta|<2.5$
  - 2 jets, $\Delta\eta> 3.5$, $E_T>30$, 20 GeV, $|\eta|<4.7$
  - $m_{JJ}>350$ GeV, $|Z|<2.5$, $\Delta\phi(\gamma\gamma,jj)>2.6$
- VBF tag definition 2012:
  - $p_T^\gamma > m_{\gamma\gamma}/2$, $m_{\gamma\gamma}/4$, $|\eta|<1.44$ or $1.57<|\eta|<2.5$
  - 2 jets, $|\eta|<4.7$, $\Delta\eta> 3$
    - $E_T>30$, 30 GeV, $m_{JJ}>500$ GeV
    - $E_T>30$, 20 GeV, $m_{JJ}>250$ GeV
  - $|Z|<2.5$, $\Delta\phi(\gamma\gamma,jj)>2.6$

Crunching numbers

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)	
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)		
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3	$\pm$ 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5	$\pm$ 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8	$\pm$ 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6	$\pm$ 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7	$\pm$ 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4	$\pm$ 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7	$\pm$ 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2	$\pm$ 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5	$\pm$ 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3	$\pm$ 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7	$\pm$ 0.4

Mass spectra

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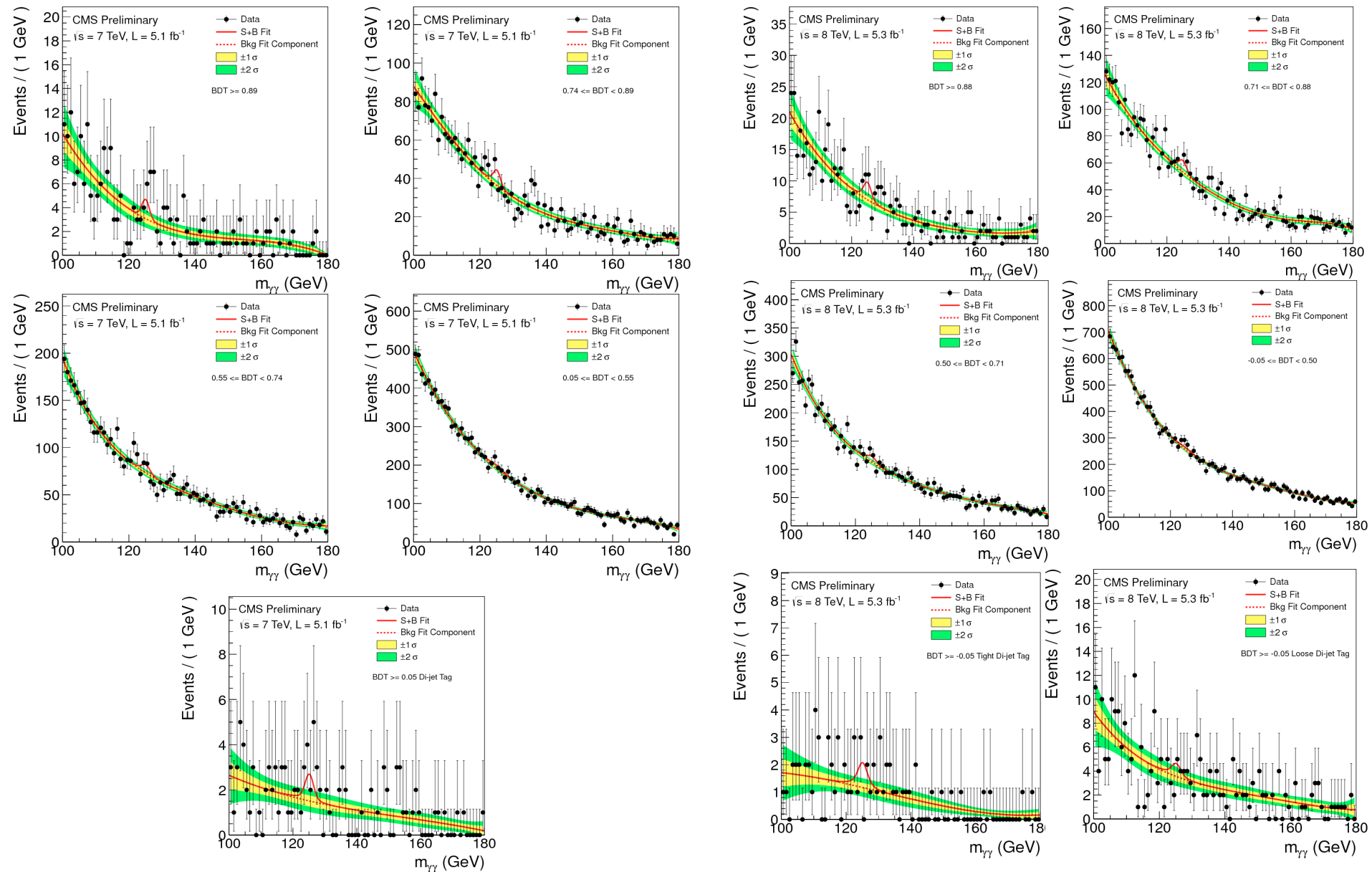
Visual aid
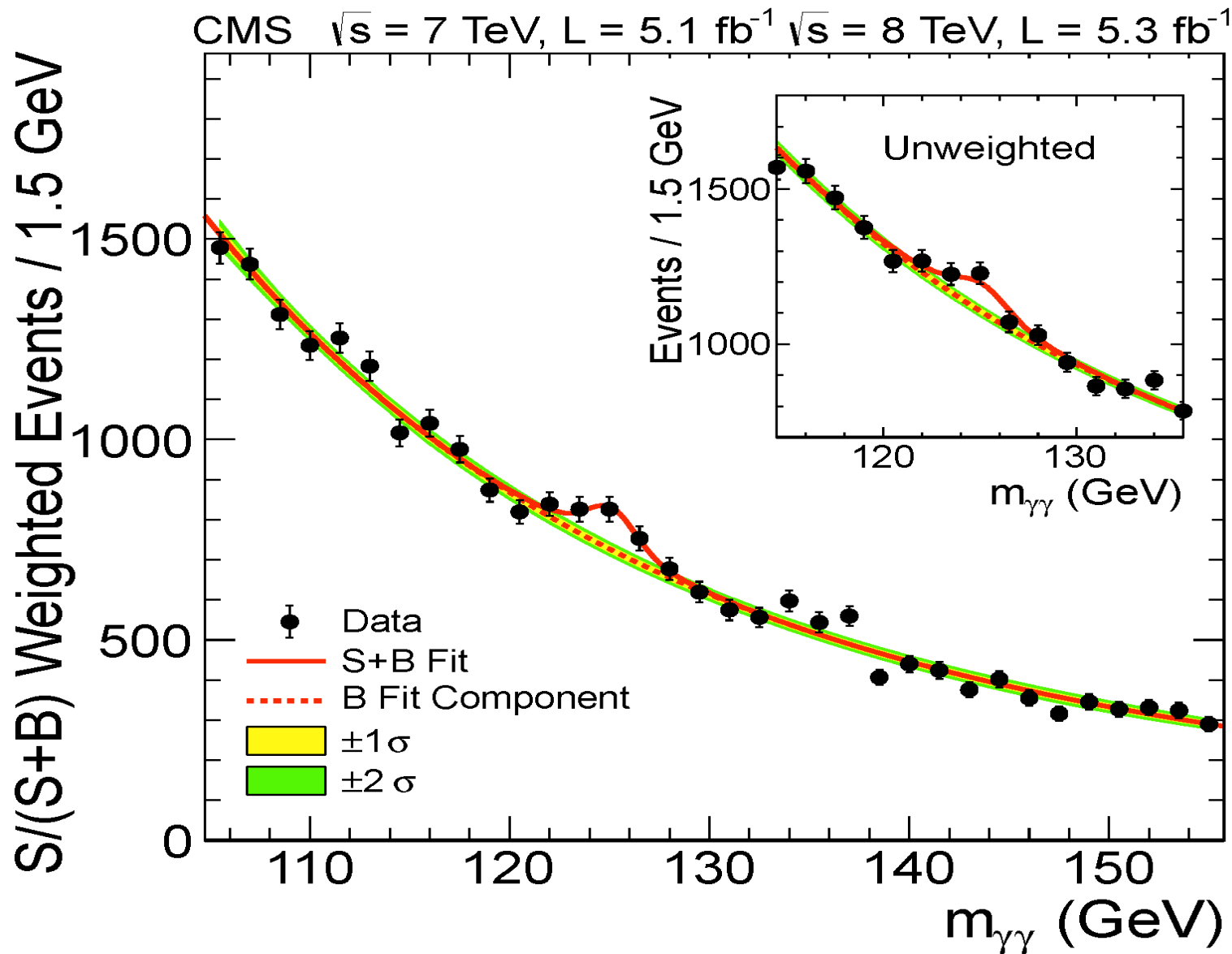
| Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Photon selection efficiency		0.8%	2.2%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.60%	0.90%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.52%
Energy scale (($E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.19%, 0.71%	0.88%, 0.19%
	$R_9 < 0.94$ (low η, high η)	0.13%, 0.51%	0.18%, 0.28%
Photon identification BDT		±0.01 (shape shift)	
(Effect of up to 4.3% event class migration.)			
Photon energy resolution BDT		$\pm10\%$ (shape scaling)	
(Effect of up to 8.1% event class migration.)			
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	50%	
(Effect of up to 15% event migration among dijet classes.)			
Production cross sections		Scale	PDF
Gluon-gluon fusion		+12.5% -8.2%	+7.9% -7.7%
Vector boson fusion		+0.5% -0.3%	+2.7% -2.1%
Associated production with W/Z		1.8%	4.2%
Associated production with $t\bar{t}$		+3.6% -9.5%	8.5%
Scale and PDF uncertainties		(y, p_T)-differential	
(Effect of up to 12.5% event class migration.)			
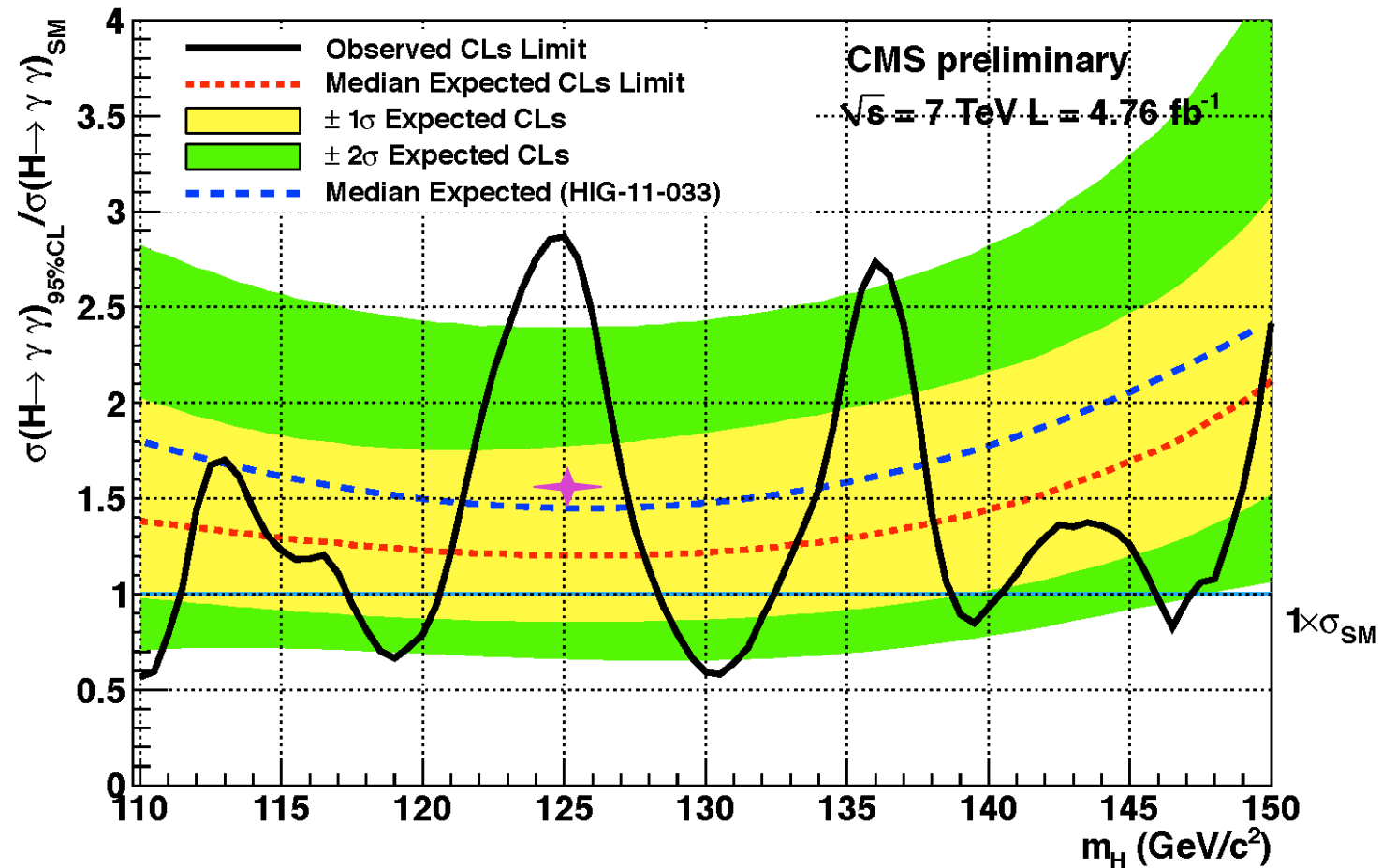
The result (7 TeV)

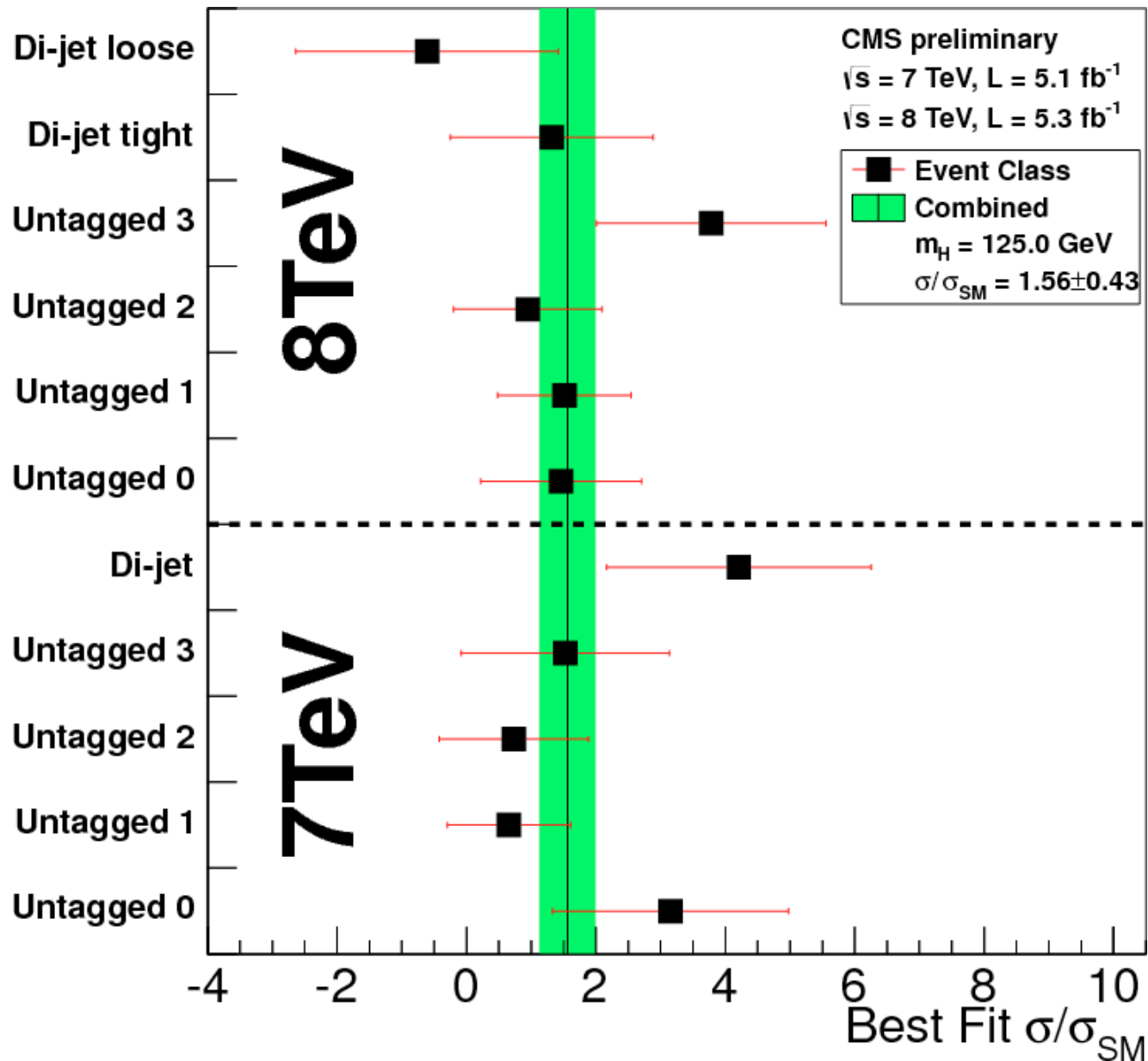New analysis methods result in effectively almost 40% larger data sample

The result

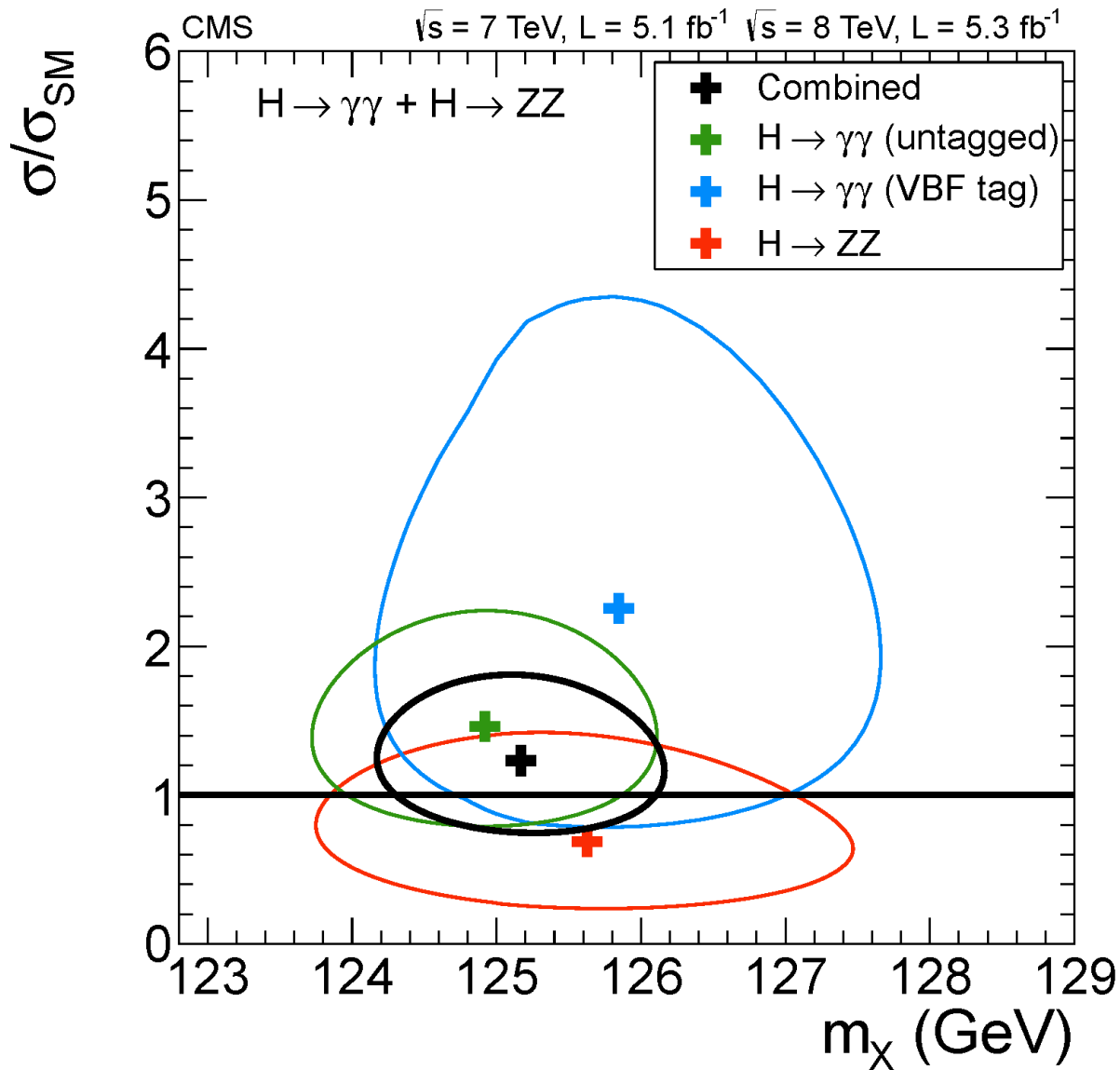Yuri Gershtein
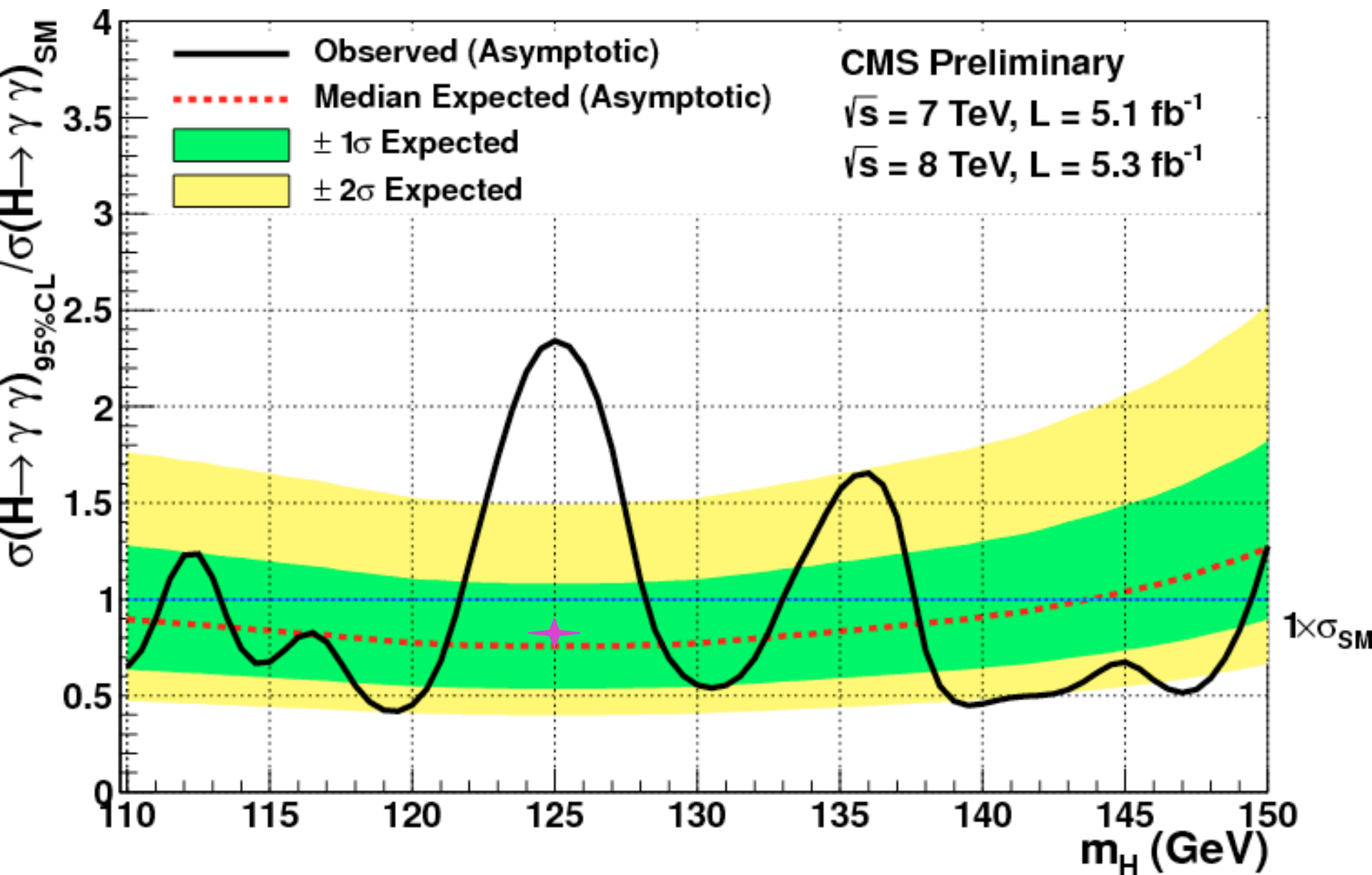
The result

The result

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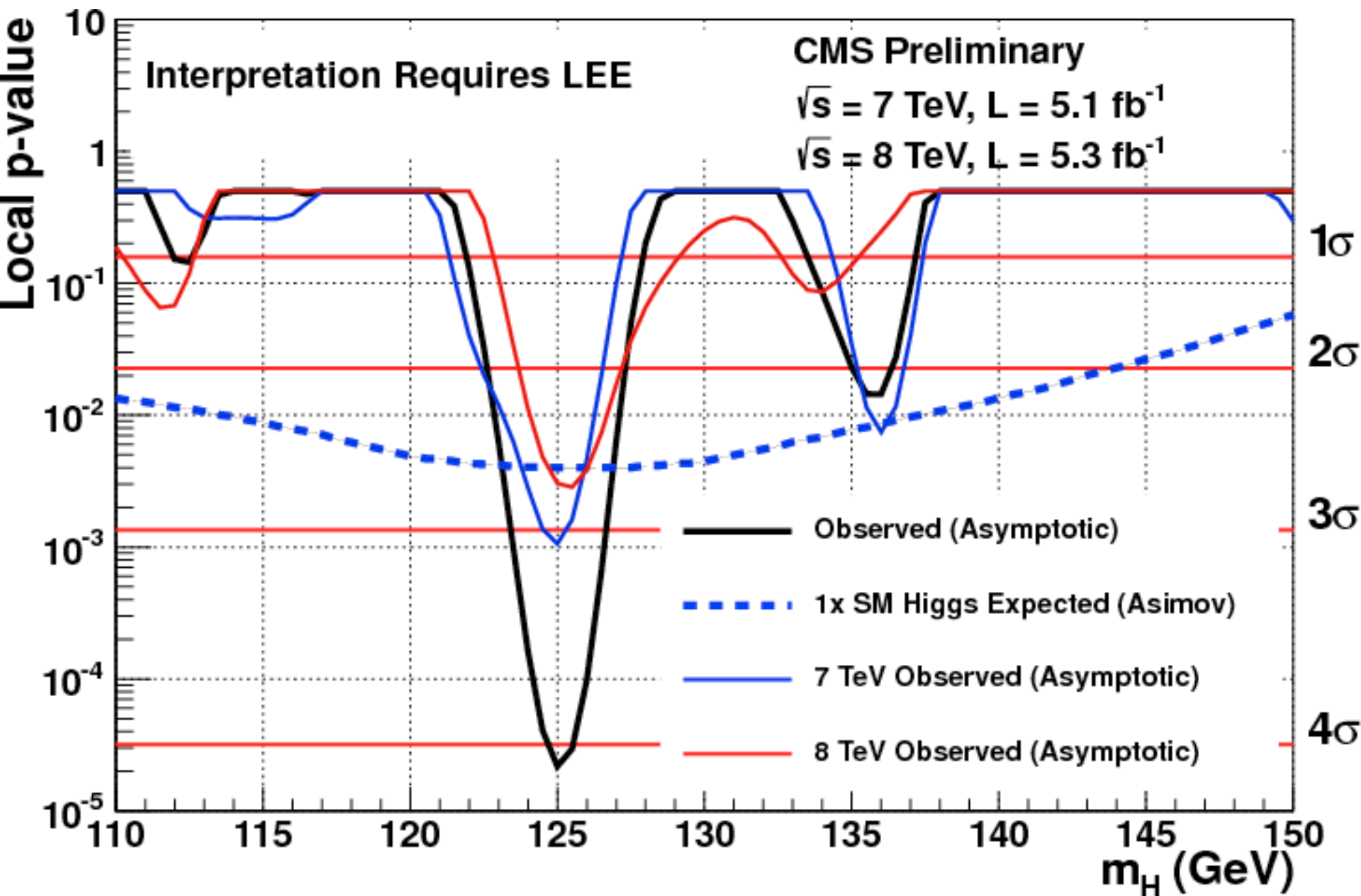
The result

Alternative scenarios

- Data consistent with SM – so far
- Doesn't mean that we should not look closer ☺
- So far just one benchmark – purely fermiophobic
  - events with leptonic tag become important (e, mu, MET)
  - gg production is essentially switched off (W loop contribution is tiny)
    - can exploit the VBF / VH kinematics – higher higgs pT in untagged events
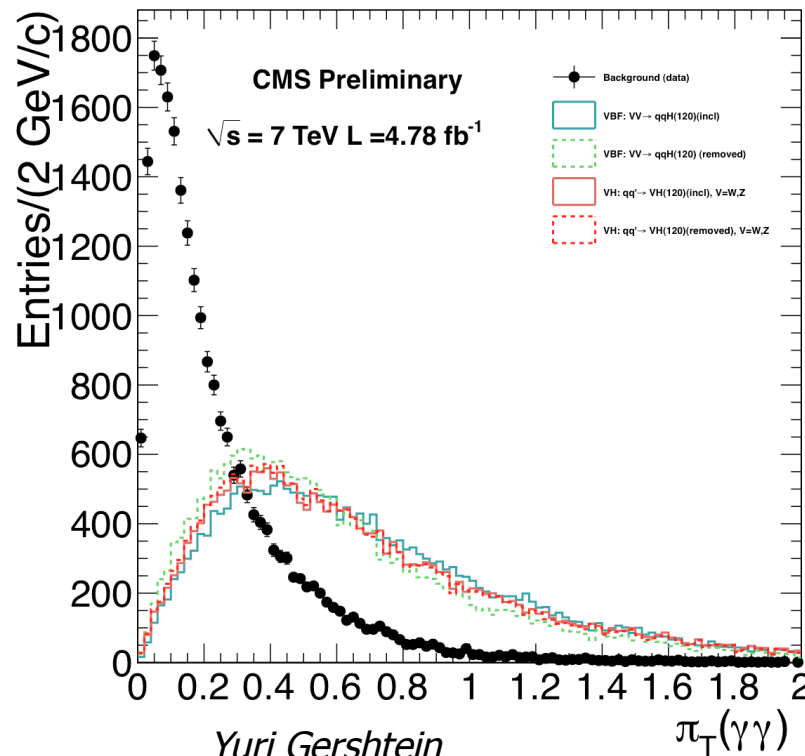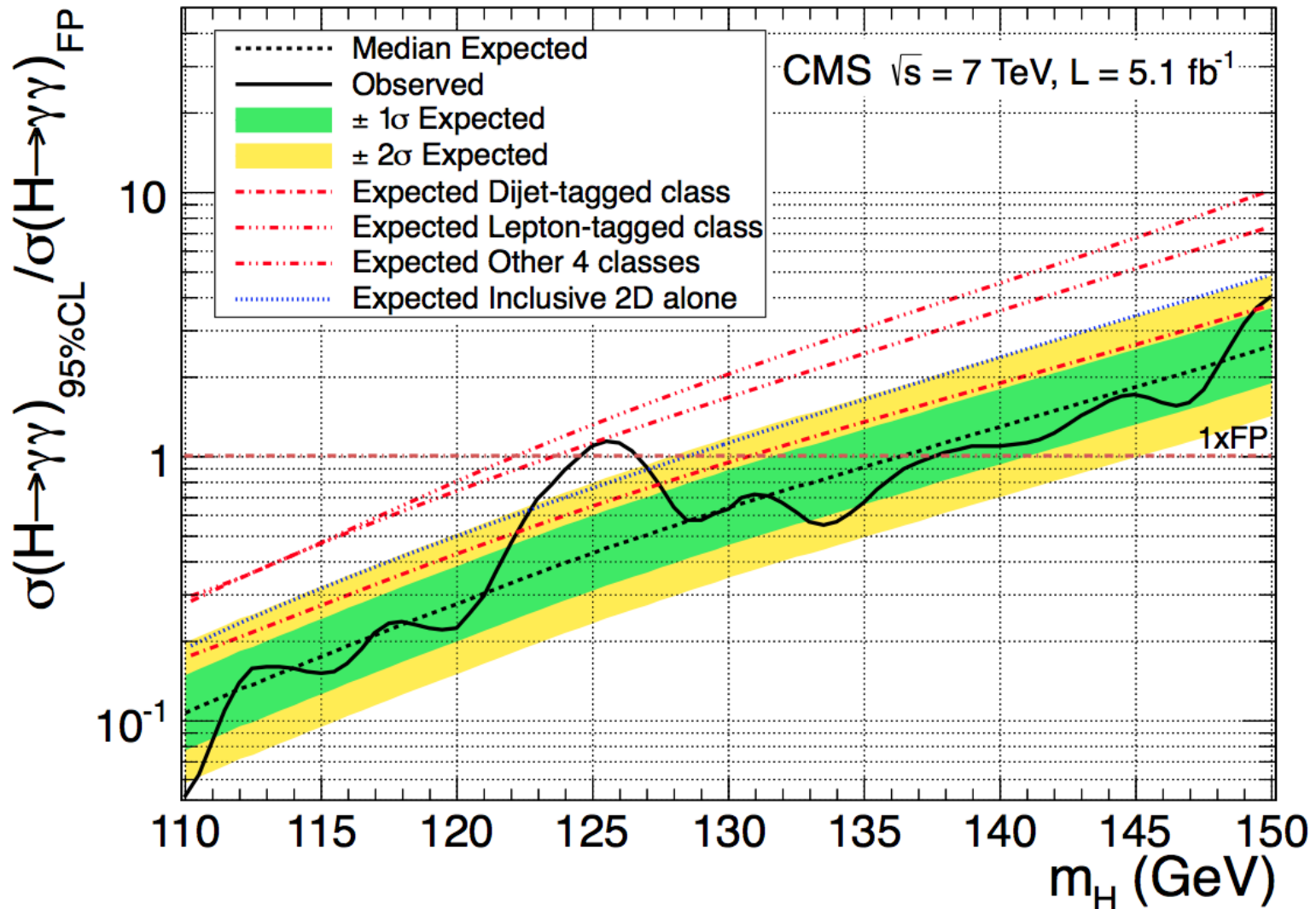
Lepton tags

$p_T > 20$ GeV, $\Delta R > 1$
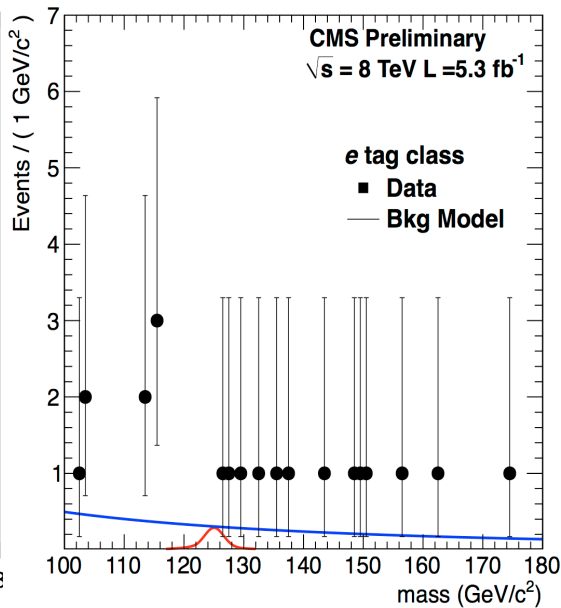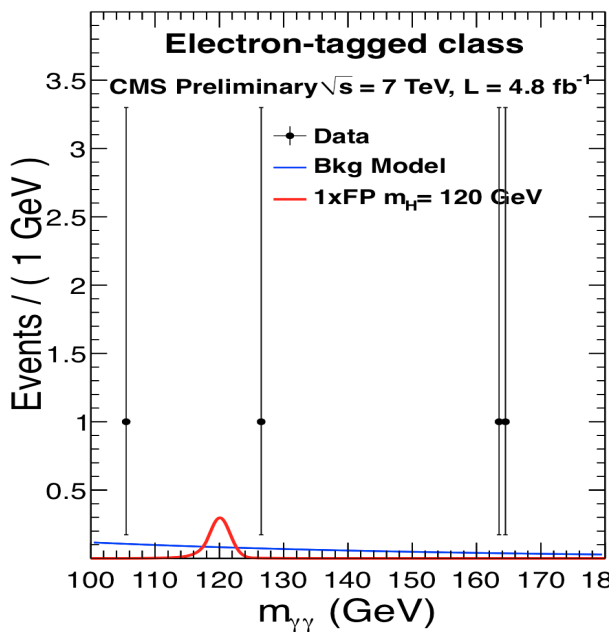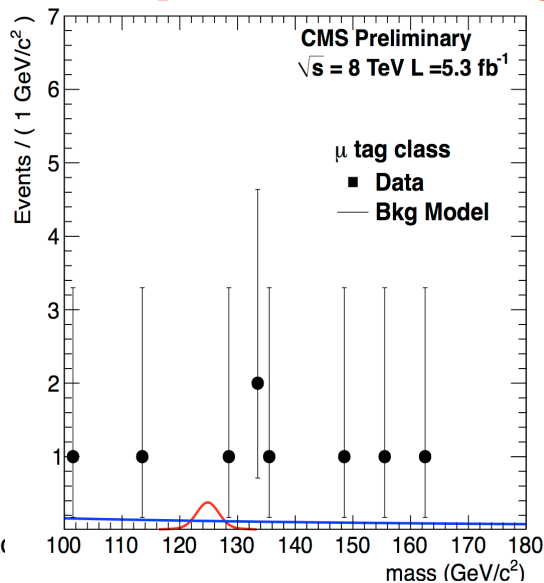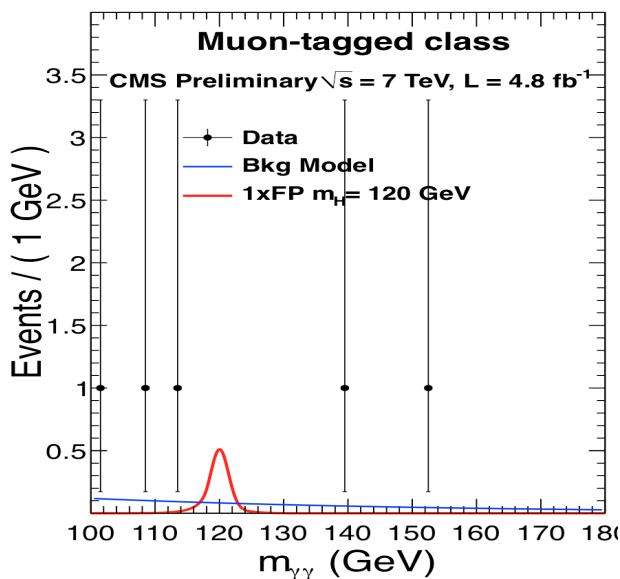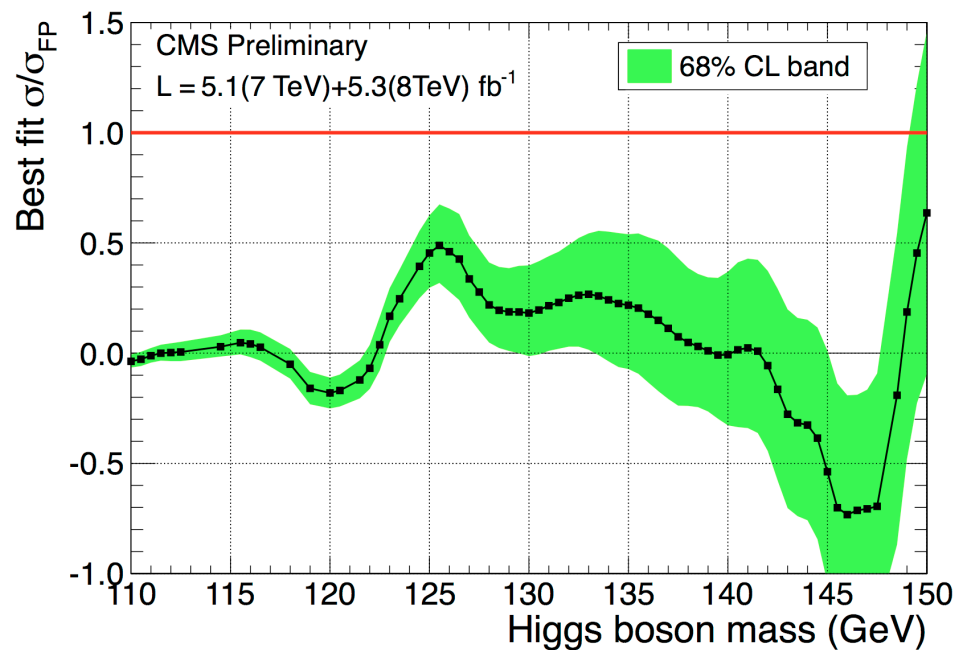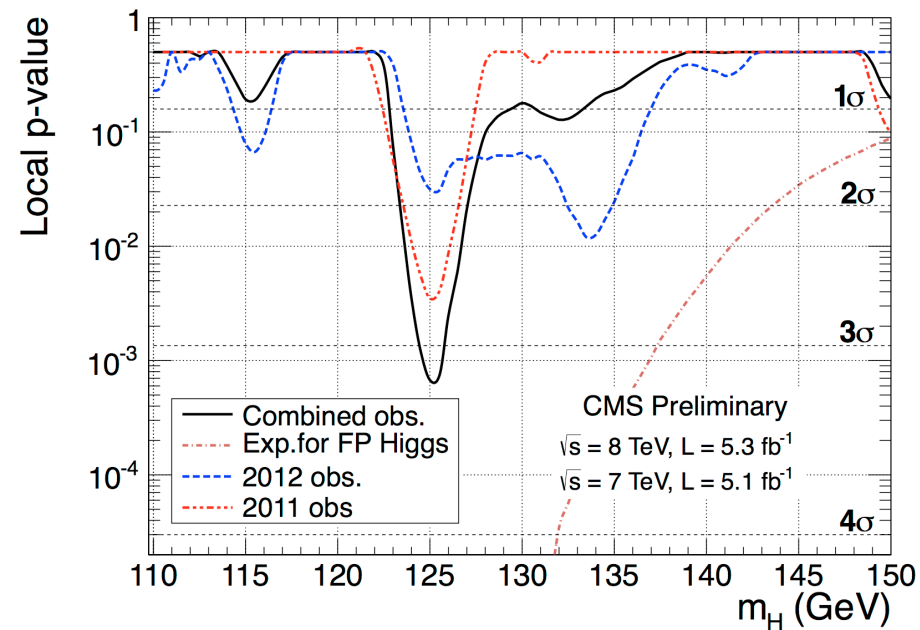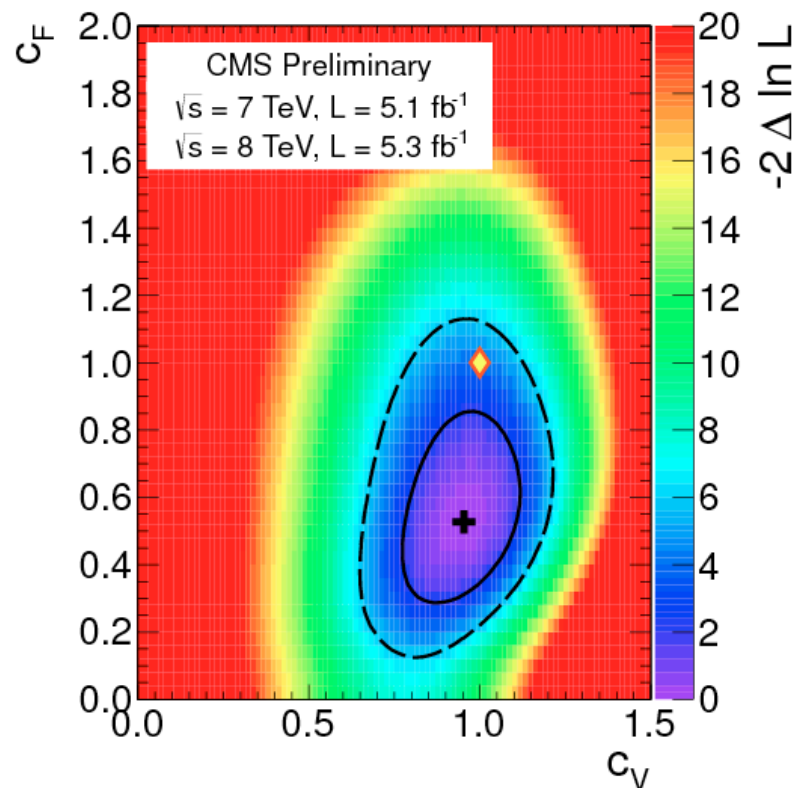

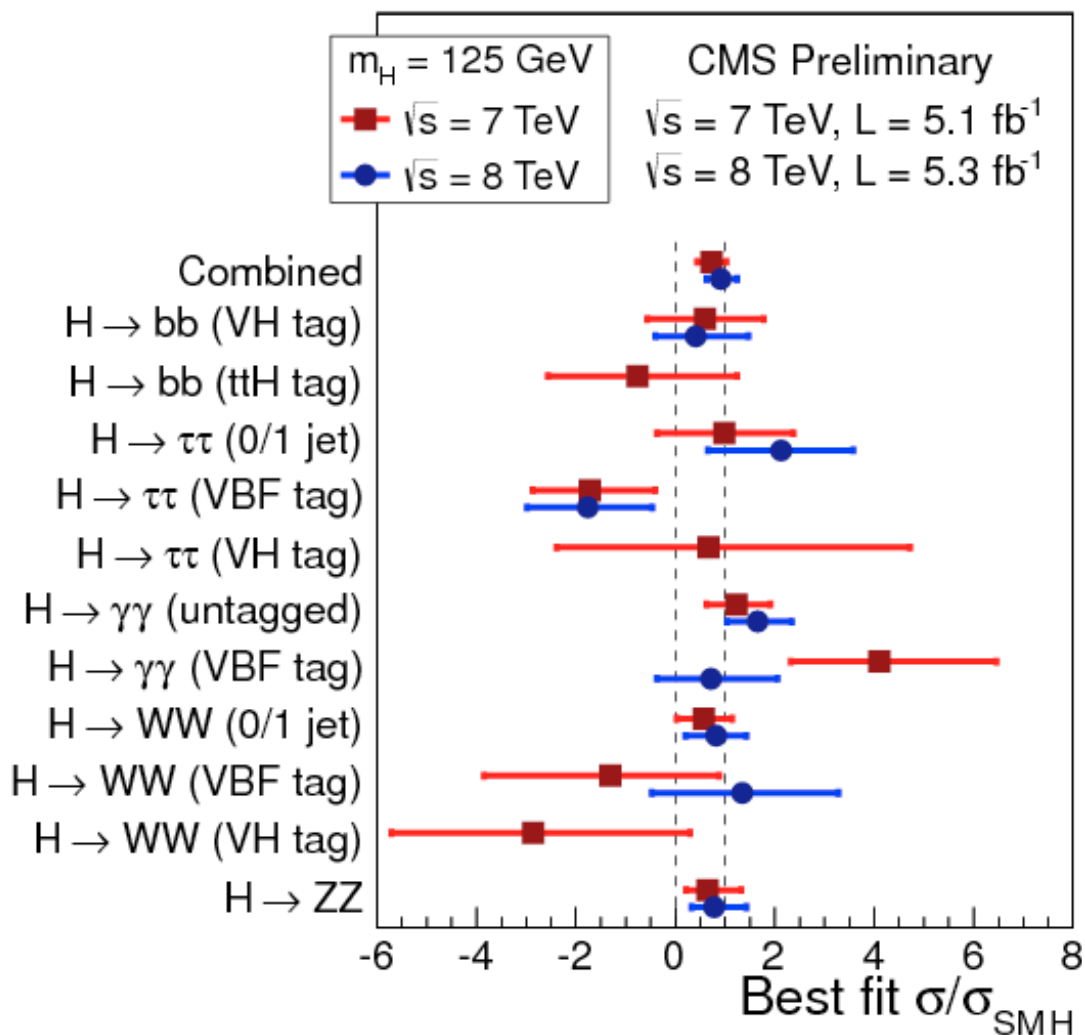MET>70 GeV
Photons in barrel
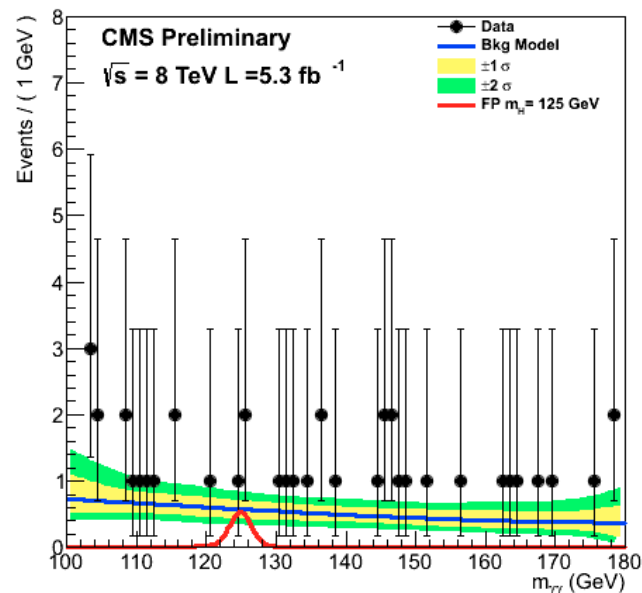
2D fit

- Now in addition to mass have the second highly discriminating variable: $\pi_T = p_T/m_{\gamma\gamma}$

Pure FP is excluded...

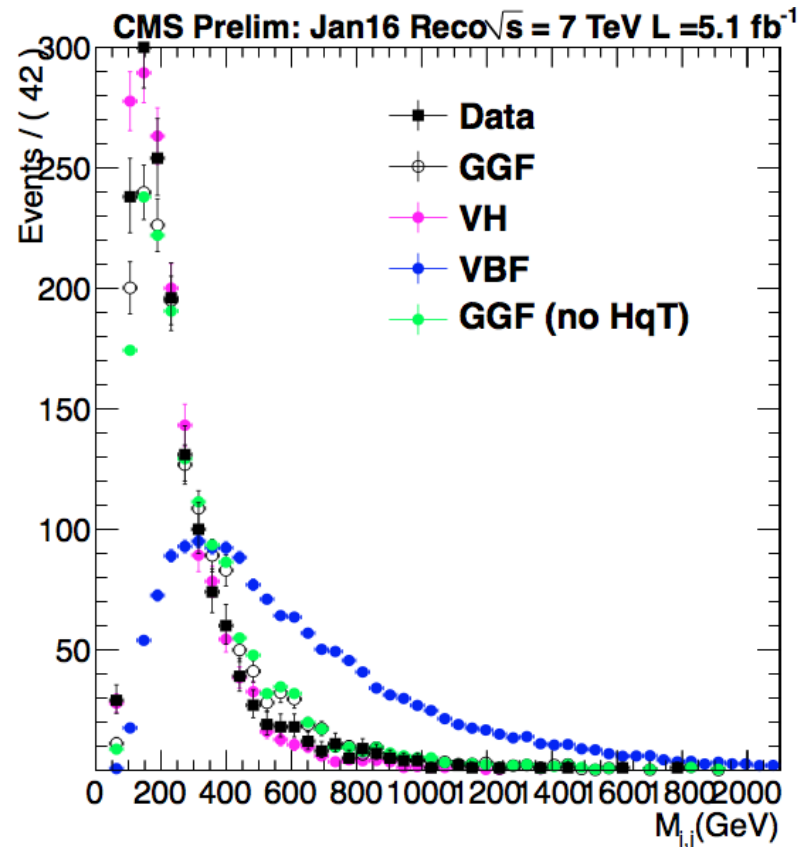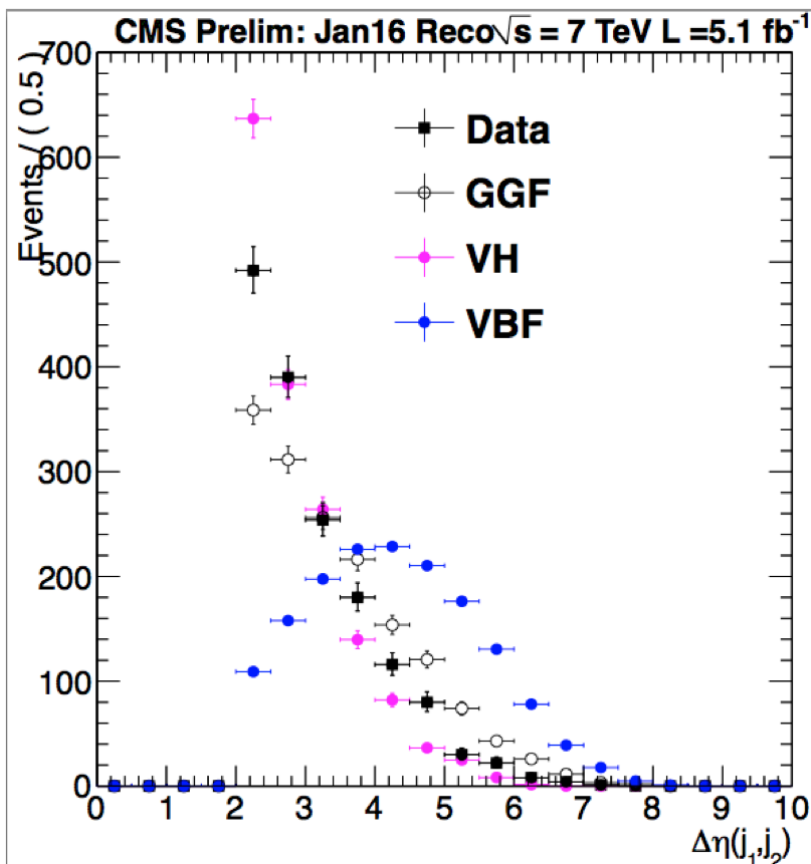# All channels

Getting cleaner VBF

- Current method of assigning systematic error to ggH -> VBF migration is akin to PDF systematics estimation circa 1990-ies: try several underlying event models and take spread as the error

- Idea – relax the $\Delta\eta$ cut and do 2D fit m($\gamma\gamma$) vs m(jj) with separate ggH and VBF components + BG. (Systematic error pumping into statistical error)

Outlook

- Now that we're sure that there is a particle at 125 GeV, the name of the game is changing
- Current analyses have SM-like signal wired in many places (i.e. event-MVA shape is sensitive to relative contributions of ggH/VBF/VH)
  - That was logical when we needed to eek out every bit of significance
  - You'll see changes may by Moriond

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